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DEVELOPMENT OF AN ELECTROCHEMICAL MACHINING PROCESS FOR RIFLING LINED GUN BARRELS

AERONUTRONIC DIVISION
PHILCO-FORD CORPORATION

TECHNICAL REPORT AFATL-TR-72-226

DECEMBER 1972

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Development Of An Electrochemical Machining Process For Rifling Lined Gun Barrels

Richard A. Harlow

David L. Corn

Richard C. Kimball

FOREWORD

This report was prepared by Philco-Ford Corporation, Aeronutronic Division, Newport Beach, California under Contract No. F08635-71-C-0209 with the Air Force Armament Laboratory, Eglin Air Force Base, Florida. The report covers work performed from June 1971 to October 1972. Mr. David Uhrig (DLDG) was program monitor for the Armament Laboratory.

This technical report has been reviewed and is approved.

Dale M Davis

DALE M. DAVIS,
Director, Guns and Rockets Division

ABSTRACT

A 16-month program was conducted to advance high performance gun barrel technology by developing an electrochemical machining process for rifling high performance barrel liner materials. A total of 15 electrolytes and numerous electrochemical machining parameters were evaluated in conducting electrochemical machinability studies on iron-nickel-base, nickel-base, and cobalt-base superalloys, and on refractory alloys of columbium, molybdenum, tantalum, and tungsten.

Four materials (L-605, VM-103, CG-27, and alloy 718) were selected for electrochemical rifling and fabrication into caliber .220 Swift barrel liners. The rifled liners were insulated externally and assembled into outer barrel jackets using a drawing process, thus producing insulated composite test barrels. A total of 12 test barrels compatible with an MG-3 machine gun, representing the four liner materials and three jacket materials (H-11, A-286, and Pyromet X-15), were fabricated and delivered to the Air Force. The results of this program indicated that electrochemical machining is a feasible process for obtaining high quality and low cost rifling, and that extrapolation of this process to larger calibers appears feasible.

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SECTION I

INTRODUCTION

During recent years, the necessity for improved gun barrel designs has become increasingly apparent with the inception of new high performance cased and caseless weapons. The requirements for high muzzle velocities, higher firing rates, and extended burst firing schedules have isolated barrels as perhaps the most performance-limiting gun components. The more severe service requirements not only drastically increase barrel erosion rates but also cause a potential problem of barrel overheating and possible premature structural failure.

The Air Force has funded several research and development programs with the objective of developing new barrel concepts, materials, and fabrication processes applicable to high performance weapons. Particular emphasis has been placed on fully lined barrels or barrels with partial length inserts. More recently, the insulated composite barrel has also been investigated under Contracts F08635-69-C-0156, "Equilibrium Temperature Gun Concepts"; F08635-70-C-0116, "Composite Barrel Materials Research and Development"; and a current program, Contract F08635-71-C-0181, "Development of Full Length Insulated Composite Barrels for Aircraft Machine Guns." The insulated composite barrel consists of a high temperature erosion-resistant (refractory alloy or superalloy) liner surrounded by a thin layer of ceramic insulation and encased within a high strength, lower temperature (steel or superalloy) outer jacket. The high temperature liner provides improved erosion resistance under extreme firing schedules; the insulator reduces the heat loads to the outer jacket, thereby providing a capability for more severe firing schedules without structural failure or a significant increase in barrel weight. All this Air Force work involving superalloy and refractory metal liners as well as internally funded barrel technology programs at the contractor facility has pointed out a very significant need for improved fabrication processes, particularly in the areas of gun drilling and rifling. A general rule of thumb indicates that the more erosion-resistant materials are also the most difficult to fabricate by conventional techniques. In fact, valid erosion tests of some promising materials (even though they can be gun drilled with difficulty) have not been possible due to the lack of satisfactory rifling techniques.

A very promising approach to the rifling of materials that are difficult or impossible to machine is electrochemical machining. This highly production-oriented process has been widely used in aerospace industries for rapidly machining complex shapes for several years. In 1971, the Air Force awarded Contract F08635-71-C-0209, "Development of an Electrochemical Machining Technique for Rifling Refractory Lined Gun Barrels," with the primary objective of developing an electrochemical machining process for high temperature refractory metal and superalloy liners. This consisted

of a 16-month two-phase effort that included electrochemical machining process development and fabrication of caliber .220 Swift insulated composite test barrels with electrochemically rifled liners for delivery to the Air Force. A summary of the program and resulting conclusions and recommendations are presented in Section II. Sections III and IV present detailed procedures and results of the development effort conducted in Phases I and II, respectively.

SECTION II

SUMMARY

2.1 TECHNICAL APPROACH

The objective of the program was to develop an electrochemical machining technique for rifling gun barrels or liners fabricated from advanced superalloys and refractory metal alloys. The intent was to develop a process that could ultimately become a standard production technique for high performance gun barrels.

Phase I of the program consisted of electrochemical machinability studies wherein attempts to electrochemical machine simulated rifling grooves on samples of L-605, VM-103, Cb-752, WC-3015, T-111, TZM, and tungsten were made utilizing various combinations of electrochemical machining parameters and 15 different electrolyte compositions. The attempts on L-605, VM-103, WC-3015, and TZM were very successful. Marginal success was achieved with Cb-752 and unalloyed tungsten, but poor surface finishes resulted. The T-111 could not be machined with any of the electrolytes or electrochemical machining parameters investigated.

Concurrently, electrochemical gun-drilling was investigated wherein attempts to drill 0.21-inch-diameter by 3-inch-deep holes in samples of L-605, TZM and VM-103 were made. This effort indicated that electrochemical gun drilling of this size was not attractive due to uncontrollable tool (electrode) chatter which precluded dimensional control. However, larger caliber gun drilling appears feasible since a more rigid electrode can be used.

A stationary electrode design and the required electrochemical machining parameters were developed for caliber .220 Swift rifling of 6-inch lengths of conventionally gun-drilled and honed bars. The initial work was performed on 4130 steel, then the parameters were refined for the deliverable liner materials, L-605, Alloy 718, VM-103 and CG-27. The refractory metals, TZM and WC-3015, were replaced as deliverables by Alloy 718 and CG-27. TZM had shown very poor erosion performance under Contract F08635-71-C-0181, and acceptable WC-3015 could not be successfully fabricated within the program schedule.

Phase II involved scaling up the short-length electrodes and electrochemical machining parameters to full length (24-inch) caliber .220 Swift liners. The initial work was accomplished on 4130 and then followed by developing parameters for the deliverable L-605, VM-103, Alloy 718, and CG-27. Rifling of three liners of each material was very successful, and good dimensional control and surface finishes were achieved.

The liners were then fabricated into full length insulated composite barrels utilizing a drawing process developed under Contract F08635-71-C-0181. H-200 series zirconia insulators and jacket materials of H-11, Pyromet X-15, and A-286 were utilized. The barrels were proof-test fired and delivered to the Air Force for testing and evaluation which concluded the technical effort.

2.2 CONCLUSIONS AND RECOMMENDATIONS

Based on the effort briefly summarized above and detailed in Sections III and IV, the following conclusions and recommendations were made:

1. Electrochemical machining appears extremely attractive as a rifling process. Excellent surface finishes, good dimensional control, and very low predicted production rifling costs are potential advantages of this process.

2. It is recommended that further work be performed to extrapolate the rifling technology developed on this program to larger calibers (20 to 40mm). A significant cost saving over present conventional rifling techniques will result if successful.

3. The electrochemical machining process presently appears to be applicable to all iron, nickel, cobalt or molybdenum-base alloys, and some columbium alloys. More development work is required to electrochemical machine the remaining columbium alloys, the tantalum-base alloys, and unalloyed tungsten. Higher voltages could improve the electrochemical machining characteristics of these materials and should be investigated as a first approach, since only minor equipment modifications would be required.

4. A basic study is recommended to isolate and correlate the significant parameters of the electrochemical machining process. Electrolyte selection in this program was based entirely on past experience and empirical additions to existing solutions. A more basic understanding of the voltage-current-electrolyte relationship to the metal removal mechanism would be helpful in selection of electrolytes and current parameters.

5. Electrochemical gun-drilling should be investigated for application to larger calibers. The increased stiffness of the larger diameter electrode should reduce vibration to an acceptable minimum and thus allow this process to be applied to materials which previously could not be easily gun-drilled. Electrochemical gun-drilling could be very cost-competitive compared to conventional methods on difficult to machine materials.

SECTION III

PHASE I - FABRICATION PROCESS DEVELOPMENT

The goal for Phase I was first to determine the electrochemical machinability of various refractory alloys and superalloys, and then, based on these results, develop rifling techniques and parameters for fabricating liners in the deliverable .220 Swift barrels of Phase II The potential fabrication methods were selected such that the technology developed for the .220 Swift barrel liners would also be applicable to larger calibers.

3.1 LINER MATERIALS

Pure metals or alloys representing several classes of potential barrel liner materials were considered during Phase I. These included: (1) CG-27, an iron-nickel base intermediate temperature superalloy; (2) Alloy 718, a nickel-base intermediate temperature superalloy; (3) L-605 and VM-103, high temperature cobalt-base superalloys; (4) WC-3015 and Cb-752, columbium-base alloys; (5) TZM, a molybdenum-base alloy; (6) T-111, a high strength tantalum alloy; and finally (7) unalloyed tungsten. The intent was to determine which classes of materials could be electrochemically machined, and then to select those alloys with the highest predicted erosion resistance for development of rifling parameters adequate for fabrication of deliverable test barrels. Although the superalloys can be rifled by conventional techniques, the process is comparatively slow and costly due to their generally low machinability. Conventional rifling of Cb, Ta, and Mo alloys is extremely difficult and results in poor surface finishes. Pure tungsten has also proven very difficult to machine, although it potentially offers excellent erosion resistance.

3.2 ELECTROCHEMICAL MACHINABILITY STUDIES

The initial machinability tests consisted of electrochemical machining 0.075-inch-wide by 0.003-inch-deep by 2-inch-long grooves on the O.D. surface of the test specimens. These tests were designed to determine the basic electrochemical machinability of the materials and, in addition, permit evaluation of surface finishes obtained under electrochemical machining conditions similar to those which exist during rifling, using the stationary electrode technique. The tooling for these tests, shown in Figures 1 and 2, consisted of a slotted fiberglass epoxy block containing an adjustable copper shim. The shim could be moved up or down within the slot to obtain any desired electrode-work-piece distance. Figure 2 shows more clearly the electrical cable attachment hole in the shim and the hose fitting through which the electrolyte is pumped. This particular set-up is not

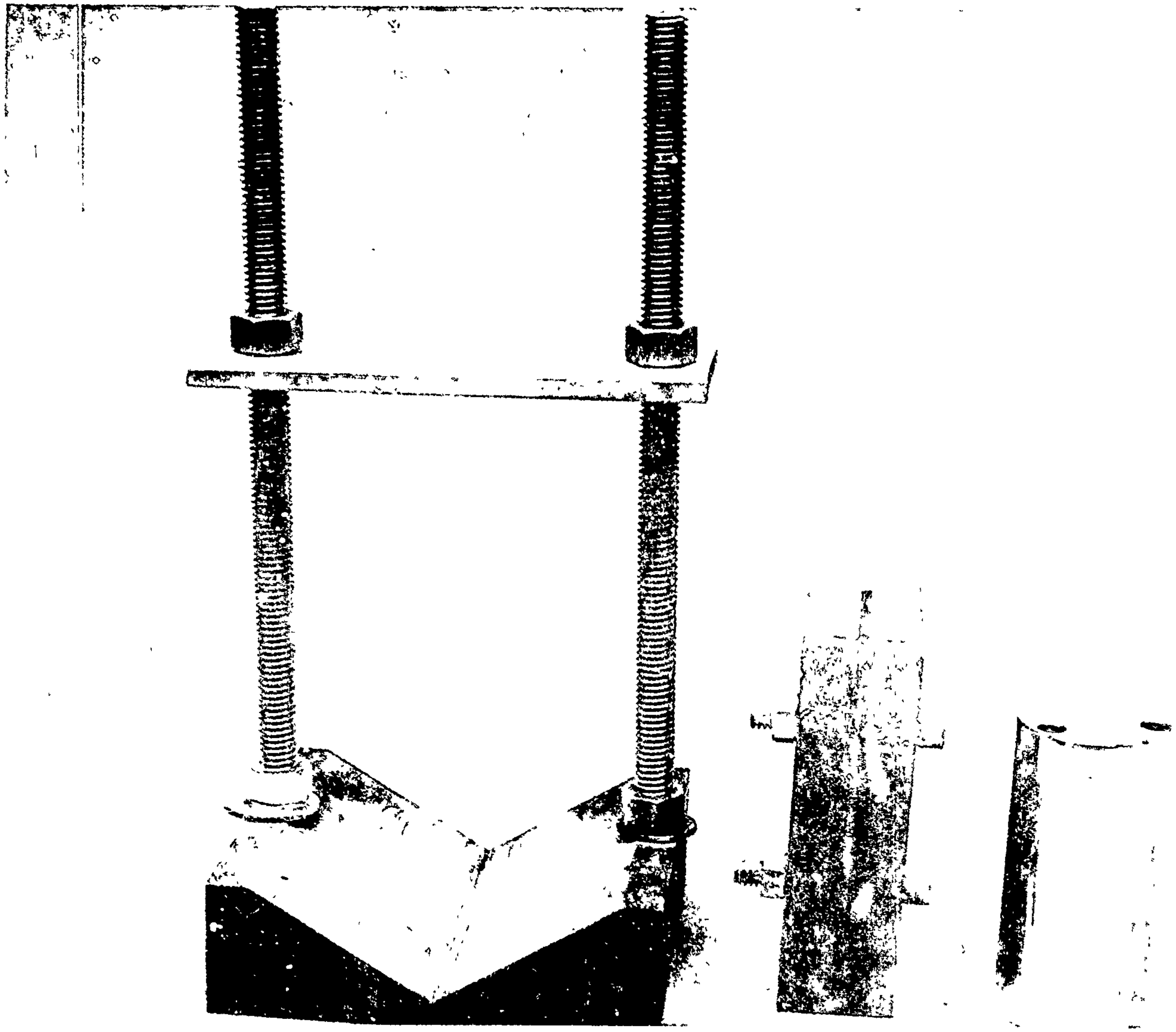


Figure 1. O.D. Rifling Test Fixture for Initial Electrochemical Machinability Studies (Disassembled)

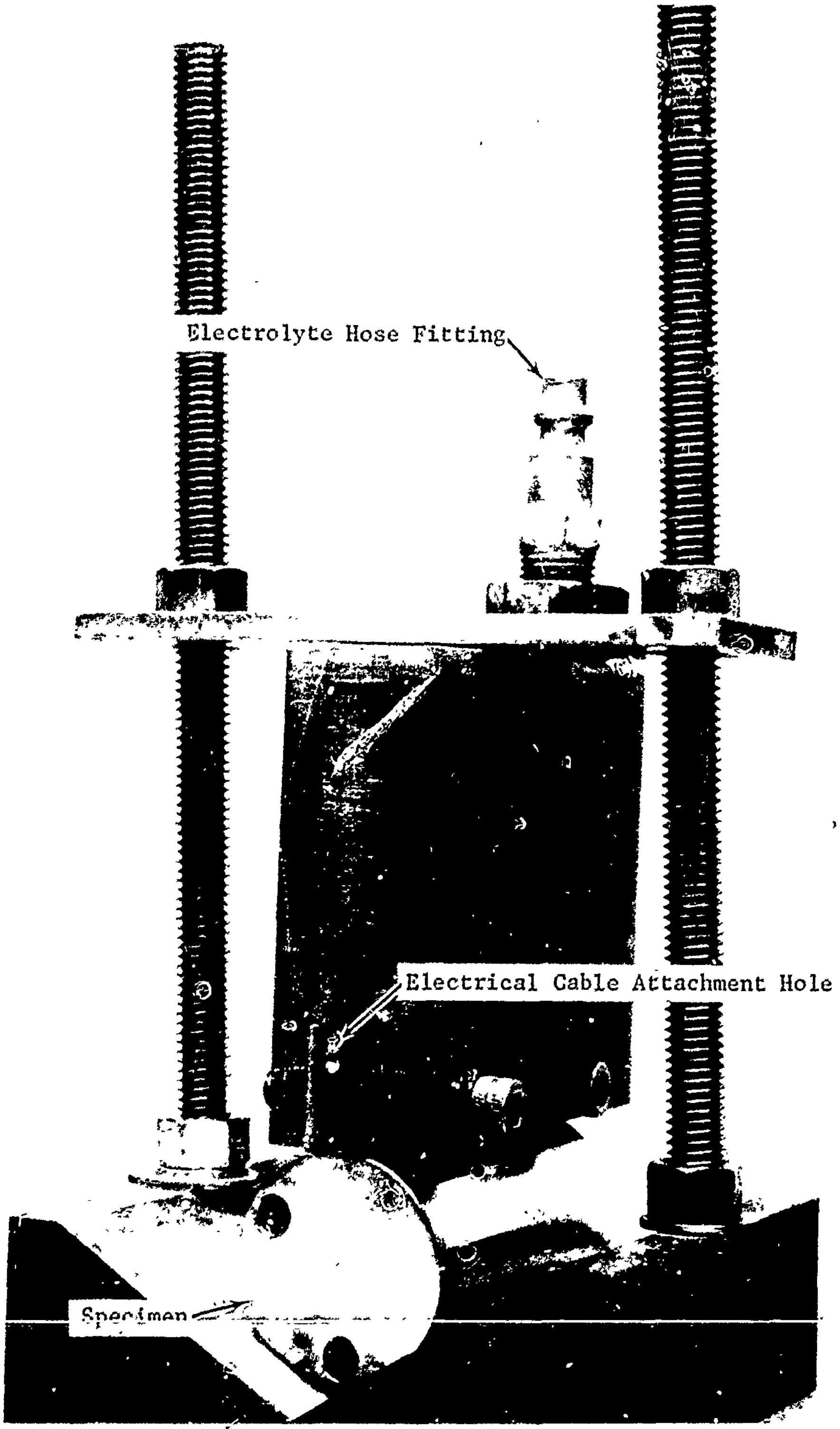


Figure 2. O.D. Rifling Test Fixture for Initial Electrochemical Machinability Studies (Assembled)

amenable to reversing the flow direction; however, for the initial machinability tests this feature was not necessary.

A total of fifteen electrolyte systems were evaluated in attempting to electrochemically machine the seven materials being considered as candidate barrel liner materials. The test conditions and electrolyte for each of the materials evaluated are given in Tables I through VI. The compositions of the fifteen electrolyte systems are given in Table VII. These electrolytes ranged from the standard sodium chloride solution to non-sludging acidic and basic electrolytes and included some special compositions that had not been previously evaluated. The special compositions were formulated in an effort to machine the alloys which did not respond to the more common systems.

Visual and metallographic examination of electrochemically machined surfaces of L-605, TZM, and VM-103 indicated that these materials could be satisfactorily machined with sodium chloride electrolyte and WC-3015 with the sodium bromide/sodium nitrite/sodium nitrate/sodium fluoride electrolyte. Pure tungsten could be machined with sodium hydroxide electrolyte, but a satisfactory surface finish could not be consistently obtained. Cb-752 could be machined with the sodium bromide/sodium nitrite electrolyte. Again a satisfactory surface finish could not be obtained consistently. T-111 could not be machined with any of the fifteen electrolyte systems evaluated. The seven pieces of material evaluated during this portion of the program are shown in Figure 3.

Photomicrographs of acceptable groove cross-sections machined in L-605, TZM, VM-103, and WC-3015 are shown in Figures 4 through 7, respectively. No intergranular attack was observed for any of these alloys. The radius of curvature at the surface intersection and the bottom of the groove was about 0.006- to 0.010-inch whereas at the groove-bore intersection the edge still appeared sharp at 250X. This geometry probably does not differ enough from conventionally machined radii to significantly change the projectile spin-up and obturation characteristics of the gun barrel. Photographs of the surface of typical grooves machined in L-605, TZM, VM-103, WC-3015, and Cb-752 during the O.D. rifling machinability tests are shown in Figures 8 through 12, respectively.

It should be mentioned that the maximum voltage used in conjunction with these electrolytes was 30 volts D.C. which is low compared to currently available D.C. power supplies. The lack of success with T-111 may be attributed to insufficiently high voltage. Electrochemical machining technology has not been sufficiently expanded to date to predict the importance of this variable; however, indications are that it might be significant based on the behavior obtained in this investigation. Going to higher voltages presents other problems (such as an increased chance of electrode arcing); however, these could probably be overcome.

TABLE I. O.D. ELECTROCHEMICAL RIFLING PARAMETERS FOR INITIAL MACHINABILITY TESTS WITH L-605

Test No.	Volts	Amperes	Power-on Time sec	Electrolyte			Remarks
				Type	Pressure psi	Temperature °F	
A-1	15	40	15	A	30	100	Electrode 0.015 inch from workpiece. Did not machine at end of groove.
A-2	15	40	15	A	30	100	2 seconds on 1 second off for 21 seconds plus one final pulse of 1 second.
A-3	15	40	15	A	30	100	Electrode 0.030 inch from workpiece.[a] Groove looked good.
A-4	15	32	8	B	30	105	Groove looked good.
A-5	15	15	30	D	30	75	Groove looked good.
A-6	15	15	15	E	25	75	Groove looked good.
A-7	7.5	20	15	F	25	75	Groove looked good.
A-8	7.5	30	10	G	25	75	Groove looked good.
A-9	15	30	15	H	25	75	Surface of groove rough.

[a] 0.030 inch electrode distance was used on all subsequent trials.

TABLE II. O.D. ELECTROCHEMICAL RIFLING PARAMETERS FOR INITIAL MACHINABILITY TESTS WITH TZM

Test No.	Volts	Amperes	Power-on Time sec	Electrolyte			Remarks
				Type	Pressure psi	Temperature °F	
B-1	15	40	10	A	30	100	Groove looked good.
B-2	15	40	10	B	30	105	Groove looked good.
B-3	15	20	30	D	30	75	Groove looked good.
B-4	15	20	15	E	25	75	Groove looked good. Not very deep.
B-5	25	30	15	E	25	75	Groove looked good.
B-6	7.5	25	15	F	25	75	Groove looked fair.
B-7	15	40	15	F	25	75	Groove looked fair.
B-8	7.5	30	15	G	25	75	Groove looked fair.

TABLE III. O.D. ELECTROCHEMICAL RIFLING PARAMETERS FOR INITIAL MACHINABILITY TESTS WITH PURE TUNGSTEN

Test No.	Volts	Amperes	Power-on Time sec	Electrolyte			Remarks
				Type	Pressure psi	Temperature °F	
1	15	10	15	A	30	100	Did not machine.
2	25	18	30	B	30	105	Did not machine.
3	25	10	30	D	30	75	Did not machine.
4	25	10	60	E	25	75	Did not machine.
5	25	5	60	F	25	75	Did not machine.
6	25	5	60	G	25	75	Did not machine.
7	25	20	60	I	25	75	Groove No. 1. Surface rough.
8	15	15	60	I	25	75	Groove No. 2. Surface rough.
9	15	25	30	J	25	75	Groove No. 3. Surface rough.
10	15	25	30	K	25	75	Groove No. 4. Surface rough.
11	25	5	60	H	25	75	Did not machine.
12	30	5	120	N	25	75	Did not machine.

TABLE IV. O.D. ELECTROCHEMICAL RIFLING PARAMETERS FOR INITIAL MACHINABILITY TESTS WITH WC-3015

Test No.	Volts	Amperes	Power-on Time sec	Electrolyte Type	Electrolyte Pressure psi	Electrolyte Temperature °F	Remarks
1	15	7-10	15	A	30	100	Just did mark workpiece. Large amount of sludge on workpiece.
2	15	7-10	30	A	30	100	Cycled current forward and reverse. 2 seconds each direction for 30 seconds. Very shallow groove.
3	25	20	30	B	30	105	Large amount of sludge on workpiece. Very shallow groove.
4	25	a	30	D	30	75	Did not machine.
5	25	7-10	30	E	25	75	Very shallow groove. Sludge on workpiece.
6	15	32	30	H	25	75	Groove looked good.
7	15	35	15	H	25	75	Groove looked good, but was shallow.
8	10	10	60	H	25	100	Groove slightly rough.
9	12.5	24	30	H	25	100	Groove looked good, but was rough on edges.

[a] Not measured.

NOTE: Electrolytes F, G, I, J, and K would not machine WC-3015.

TABLE V. O.D. ELECTROCHEMICAL RIFLING PARAMETERS FOR INITIAL MACHINABILITY TESTS WITH Cb-752

Test No.	Volts	Amperes	Power-on Time sec	Electrolyte Type	Electrolyte Pressure psi	Electrolyte Temperature °F	Remarks
1	15	a	60	H	25	75	Machined slightly.
2	25	40	30	H	25	75	Machined groove, but was very rough.
3	20	15	30	H	25	75	Machined slightly.
4	30	45	20	H	25	75	Groove rough.
5	30	45	30	H	25	75	Groove rough.
6	20	45	30	H	25	100	Groove looked fair, but walls were rough. About 0.010 inch deep.
7	20	42	10	H	25	110	Very rough.
8	25	48	15	H	25	100	Groove looked fair at entrance, but was rough at exit.
9	30	48	15	H	25	100	Groove looked fair.
10	30	45-50	15	H	25	100	Groove rough.
11	20	22	20	L	25	100	Groove rough.
12	25	47-37	15	L	25	100	Groove rough.
13	35	35-40	30	L	25	35	Amperes erratic and surface rough.

[a]Not measured.

NOTE: Electrolytes A, B, C, D, E, F, G, I, J, K, M, N, and O would not machine Cb-752.

TABLE VI. O.D. ELECTROCHEMICAL RIFLING PARAMETERS FOR INITIAL MACHINABILITY TESTS WITH VM-103

Test No.	Volts	Amperes	Power-on Time sec	Electrolyte			Remarks
				Type	Pressure psi	Temperature °F	
1	25	35	30	D	30	75	Groove looked good.
2	15	20	10	D	30	75	Groove looked good.
3	25	35	10	D	30	75	Groove looked good.
4	15	20	15	B	25	75	Groove looked good.
5	15	20	15	E	25	75	Groove looked good.
6	25	30	10	E	25	75	Groove looked good.

TABLE VII. COMPOSITIONS OF THE ELECTROLYTES EVALUATED

Type	Composition	
A	Sodium Chloride	1 lb/gal
B	Sodium Chloride	1 lb/gal
	Sodium Nitrate	3 oz/gal
	Sodium Citrate	6 oz/gal
	Rochelle Salt	4 oz/gal
C	Sodium Chloride	0.55 lb/gal
D	Sodium Nitrate	2 lb/gal
E	Sodium Chlorate	2 lb/gal
F	Sulfuric Acid	5 percent
G	Sulfuric Acid	10 percent
H	Sodium Bromide	1.5 lb/gal
	Sodium Nitrite	1.5 lb/gal
	Sodium Nitrate	0.1 lb/gal
	Sodium Fluoride	0.1 lb/gal
I	Sodium Hydroxide	2 percent
J	Sodium Hydroxide	6 percent
K	Sodium Chloride	0.5 lb/gal
	Sodium Hydroxide	0.5 lb/gal
	Rochelle Salt	0.5 lb/gal
L	Sodium Bromide	1.5 lb/gal
	Sodium Nitrite	1.5 lb/gal
	Sodium Nitrate	0.1 lb gal
	Sodium Fluoride	0.1 lb/gal
	Sodium Hydroxide	0.15 lb/gal
M	Nitric/Hydrofluoric Acid (65/35)	12-1/2 percent
N	Nitric/Hydrofluoric Acid (65/35)	25 percent
O	Nitric/Hydrofluoric Acid (65/35)	50 percent

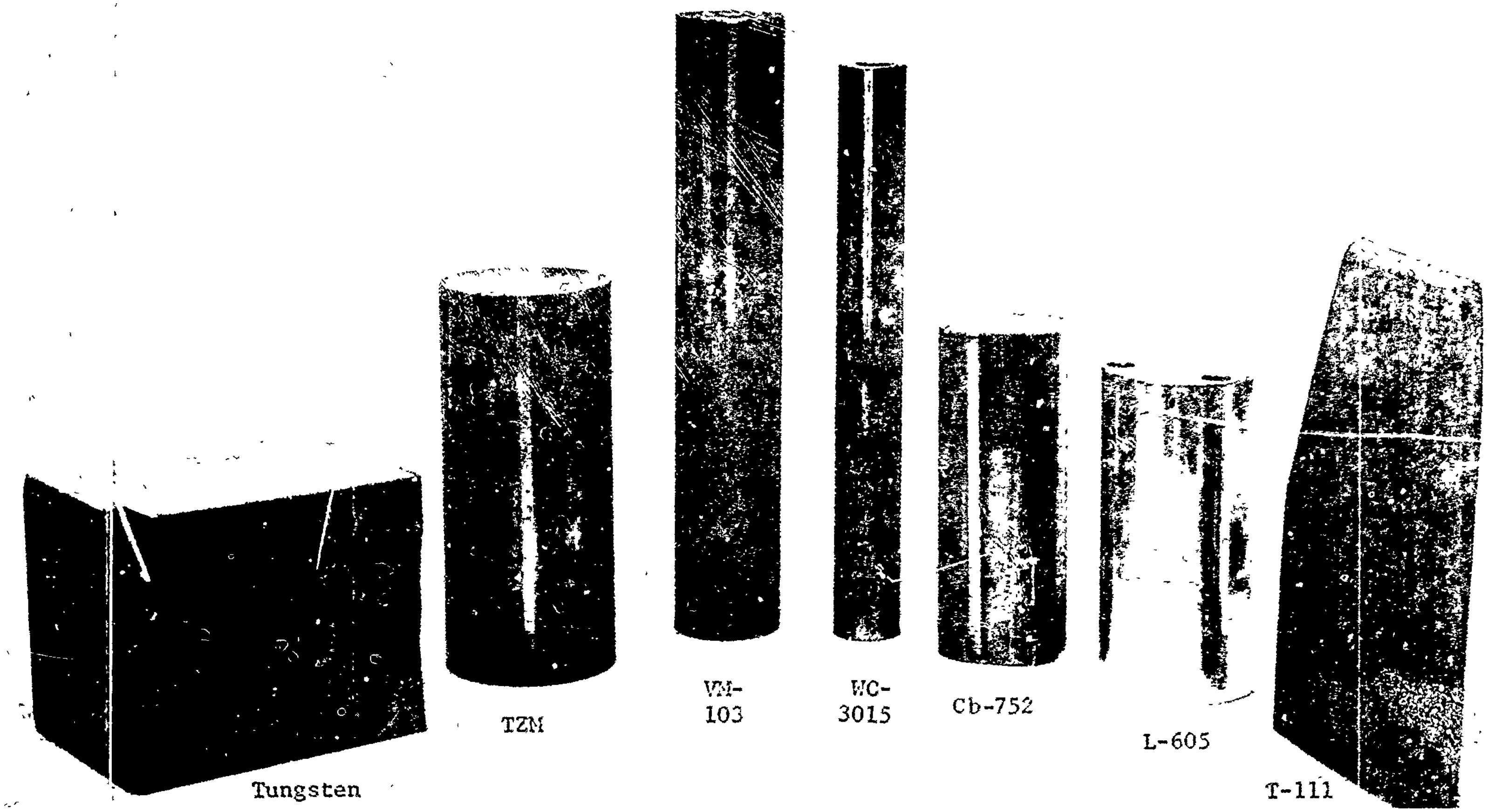


Figure 3. Test Samples Used in O.D. Electrochemical Rifling Study

Figure 4. Unetched Cross-Section of One Side of an Electrochemically Rifled Groove in L-605 (Magnification: 250X)

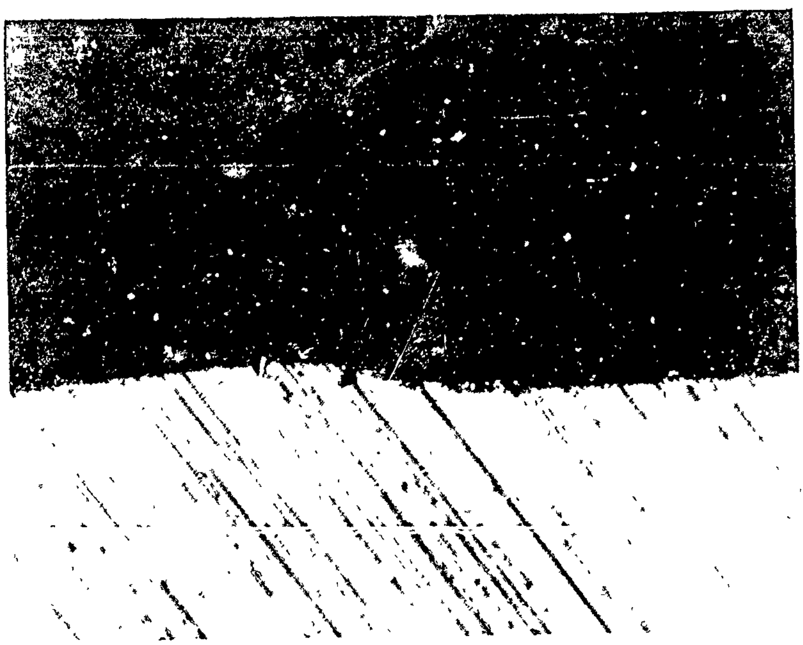


Figure 5. Unetched Cross-Section of One Side of an Electrochemically Rifled Groove in L-605 (Magnification: 250X)

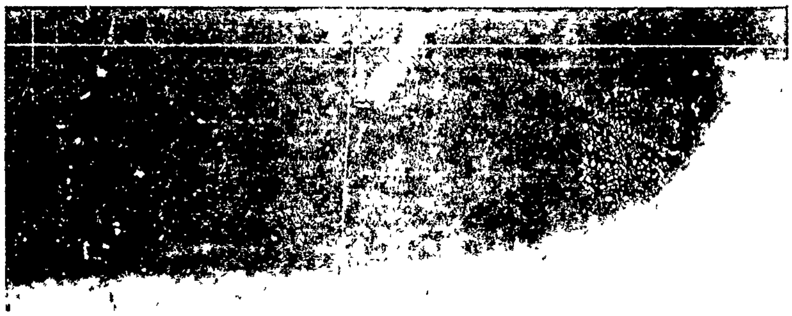
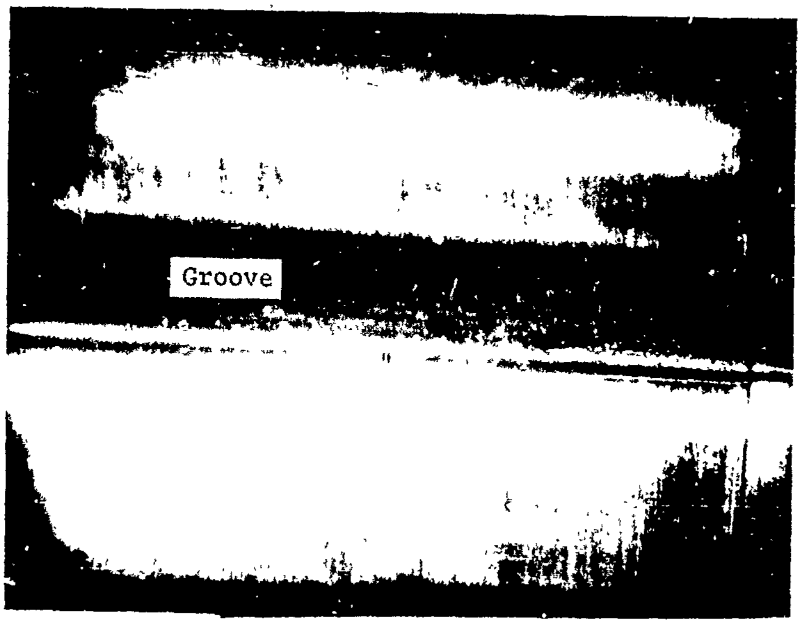
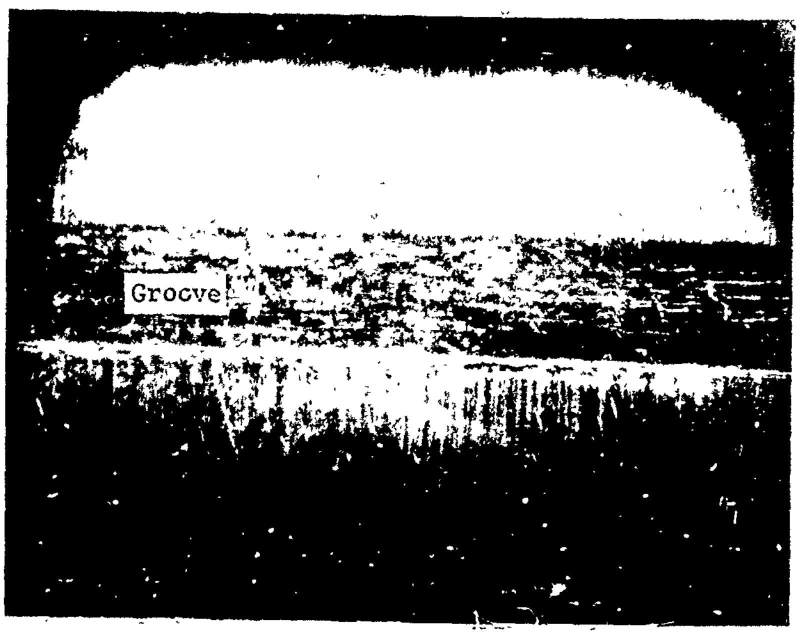


Figure 6. Unetched Cross-Section of One Side of an Electrochemically Rifled Groove in VM-103 (Magnification: 250X)

Figure 7. Unetched Cross-Section of One Side of an Electrochemically Rifled Groove in WC-3015 (Magnification: 250X)

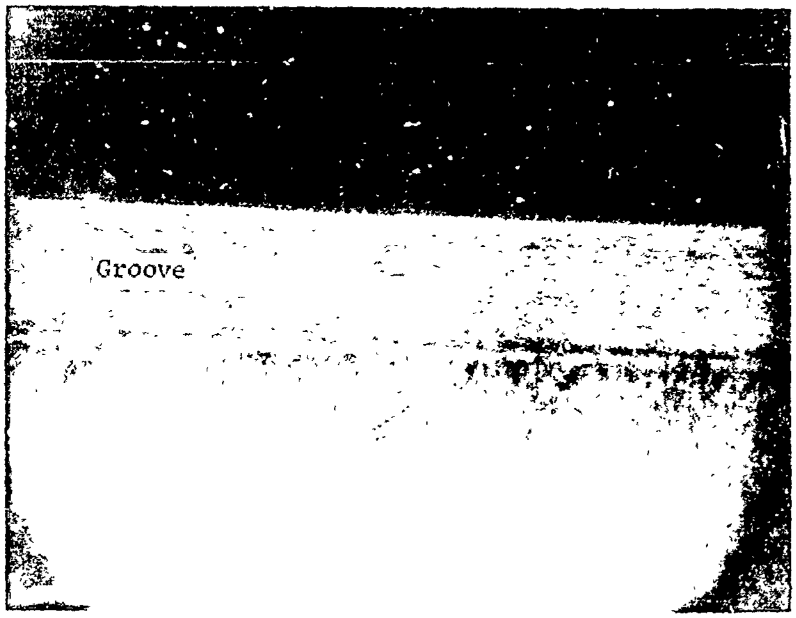


L-605 - Groove No. 2

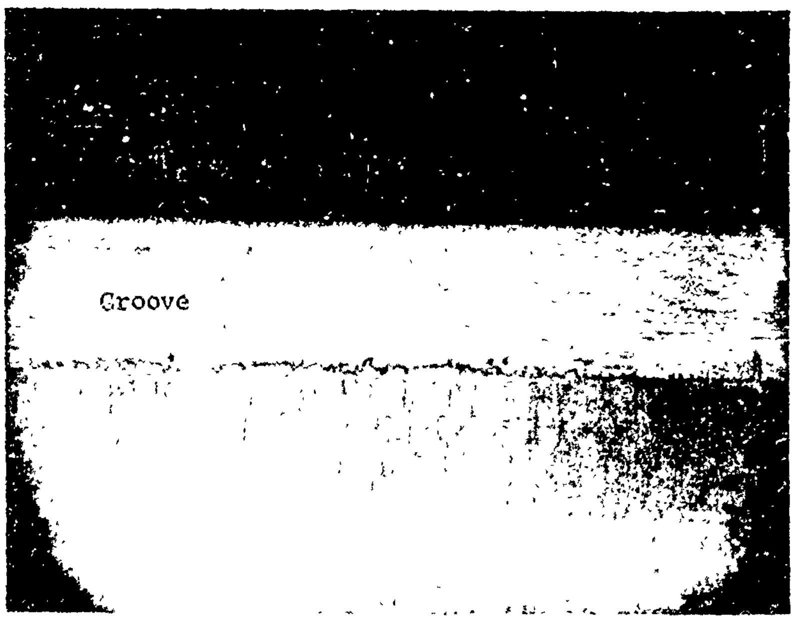


L-605 - Groove No. 4

Figure 8. Photographs of Typical O.D. Electrochemically Rifled Grooves in L-605 (Magnification: 7X)

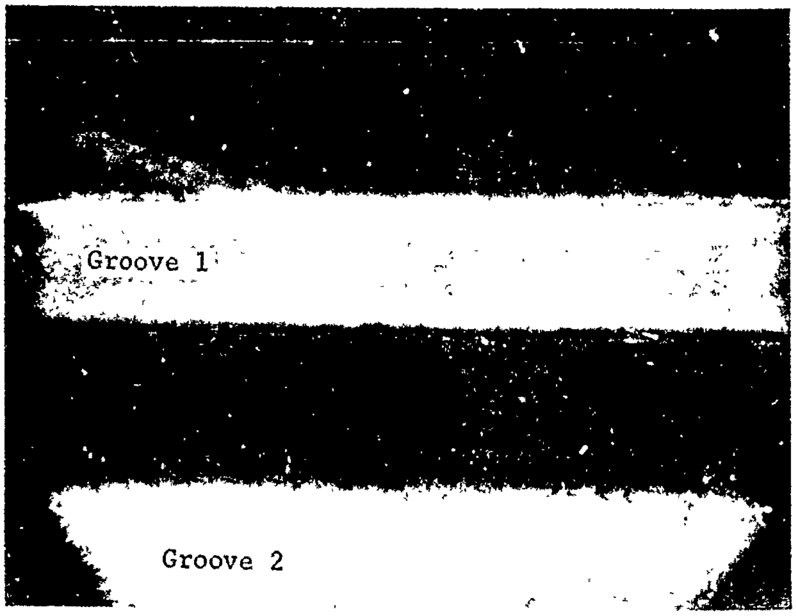


TZM - Groove No. 3

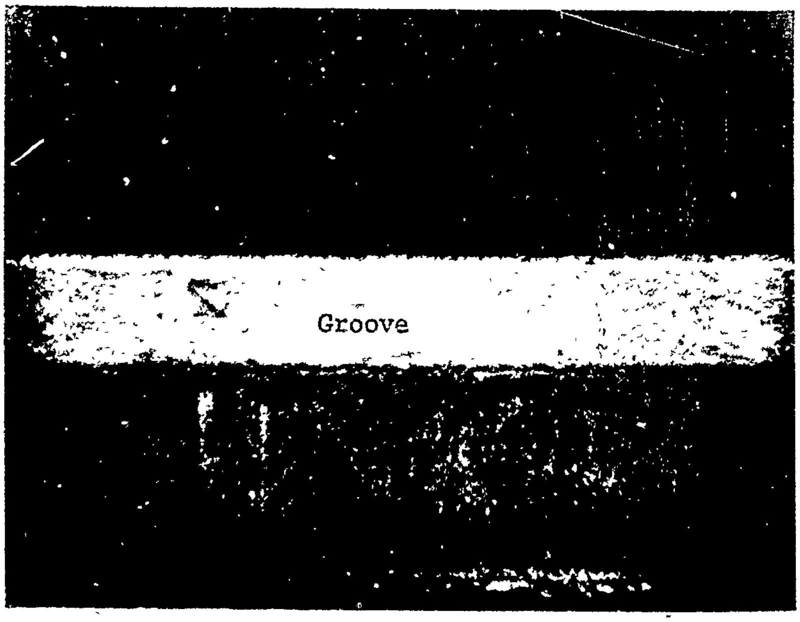


TZM - Groove No. 6

Figure 9. Photographs of Typical O.D. Electrochemically Rifled Grooves in TZM (Magnification: 7X)



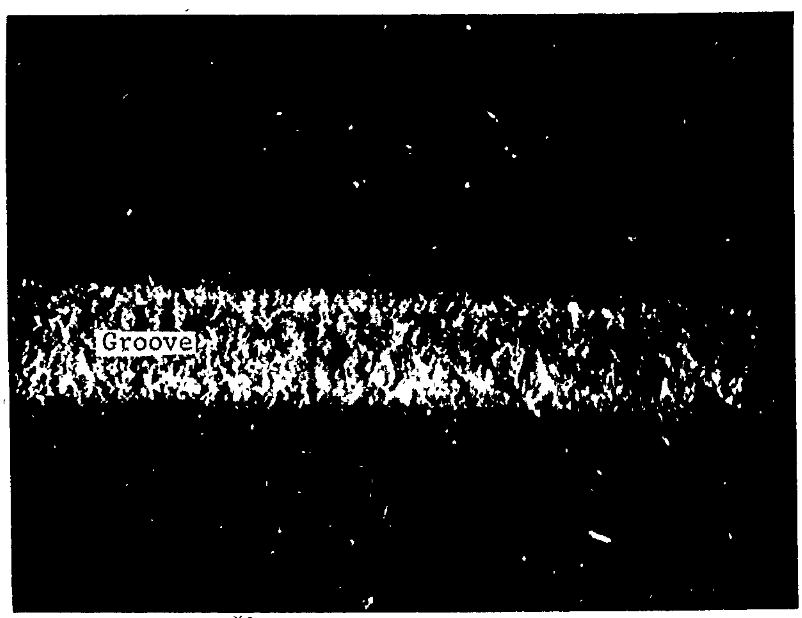
VM-103 - Groove Nos. 1 and 2



VM-103 - Groove No. 5

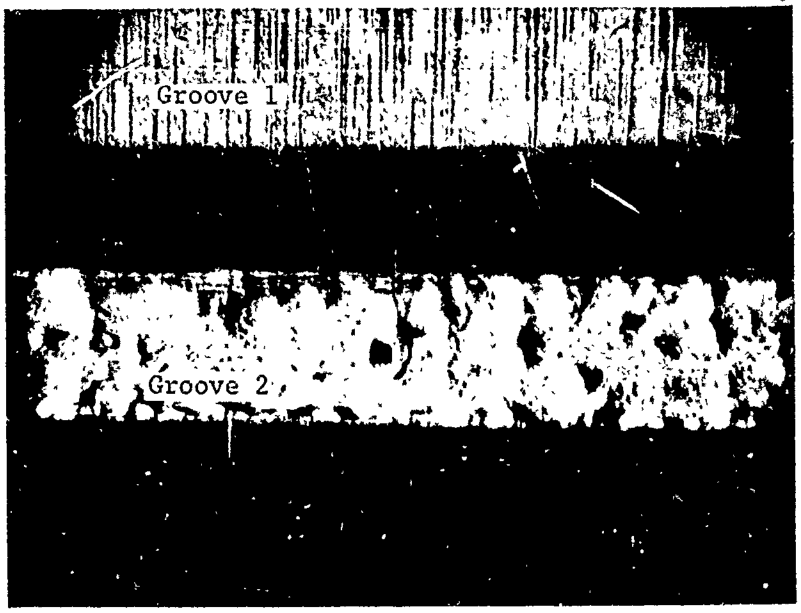
Figure 10. Photographs of Typical O.D. Electrochemically Rifled Grooves in VM-103 (Magnification: 7X)

WC-3015 - Groove No. 1



WC-3015 - Groove No. 3

Figure 11. Photographs of Typical O.D. Electrochemically Rifled Grooves in WC-3015 (Magnification: 7X)



Cb-752 - Groove Nos. 1 and 2

Cb-752 - Groove Nos. 8 and 9

Figure 12. Photographs of Typical O.D. Electrochemically Rifled Grooves in Cb-752 (Magnification: 7X)

3.3 GUN DRILLING TESTS

Since gun-drilling of superalloys and refractory metals has generally proven difficult and time-consuming, a portion of the program was directed toward establishing the feasibility of electrochemically gun drilling caliber .220 Swift liners. This investigation consisted of the development of tooling and techniques to electrochemically gun drill 0.21-inch I.D. by 3-inch-deep holes in various test materials. This tooling consisted of a 4-inch-long piece of 0.188-inch O.D. by 0.049-inch wall stainless steel tubing with a 0.200-inch O.D. by 0.090-inch I.D. by 0.030-inch-thick piece of copper-tungsten silver-soldered to one end to serve as the cutting tip. This tube was attached to a mounting plate on the electrochemical machining hardware using standard tubing fittings and served as the electrode for the drilling tests (see Figures 13 and 14). The O.D. of the tube was coated with epoxy insulation to prevent stray etching.

Electrochemical gun d illing tests were conducted with L-605, TZM, and VM-103 (Tables VIII, IX, and X, respectively) only using both a standard sodium chloride electrolyte and a sodium chloride base electrolyte containing special additives to improve machining characteristics. Problems with tool vibration (resulting in shorting of the tool and work piece) were encountered during attempts to gun drill the 0.21-inch I.D. by 3-inch-deep holes. These problems were minimized by the use of a plexiglass guide for the electrode and the addition of epoxy spacers on the outside of the electrode shank. However, vibration of the tool still persisted to an unacceptable degree. Although the resulting holes were not of acceptable quality for this caliber, they were close enough to merit serious consideration of developing electrochemical gun drilling for larger calibers where tool stiffness would be much higher. Additional evidence to support this is found in Reference 1 where five-inch gun barrels were successfully gun-drilled using the electrochemical machining process.

3.4 ELECTROCHEMICAL MACHINING RIFLING TESTS

Two different methods were considered for electrochemical rifling; i.e., rifling with either a moving or a stationary electrode. The moving electrode would be similar to an electrical discharge machining (EDM) electrode, which is translated and rotated simultaneously to achieve the desired rifling twist. This method was considered undesirable due to anticipated tool chatter which would have the same detrimental effect on dimensional control as was demonstrated with the moving gun-drilling electrode. The tooling design and fabrication complexity of this method made it appear less attractive than the stationary electrode, described below.

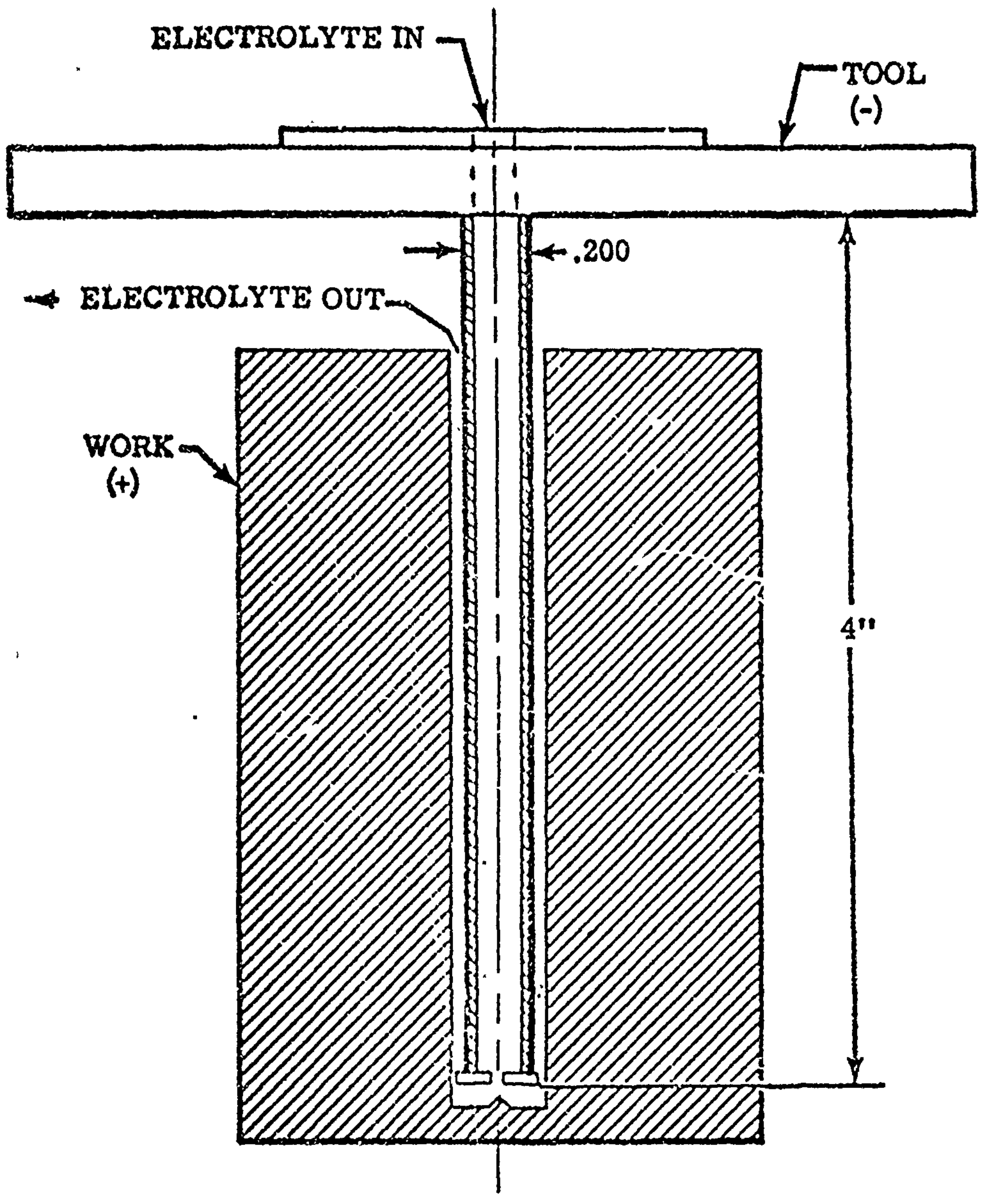


Figure 13. Sketch of Electrochemical Gun-Drilling Test Apparatus

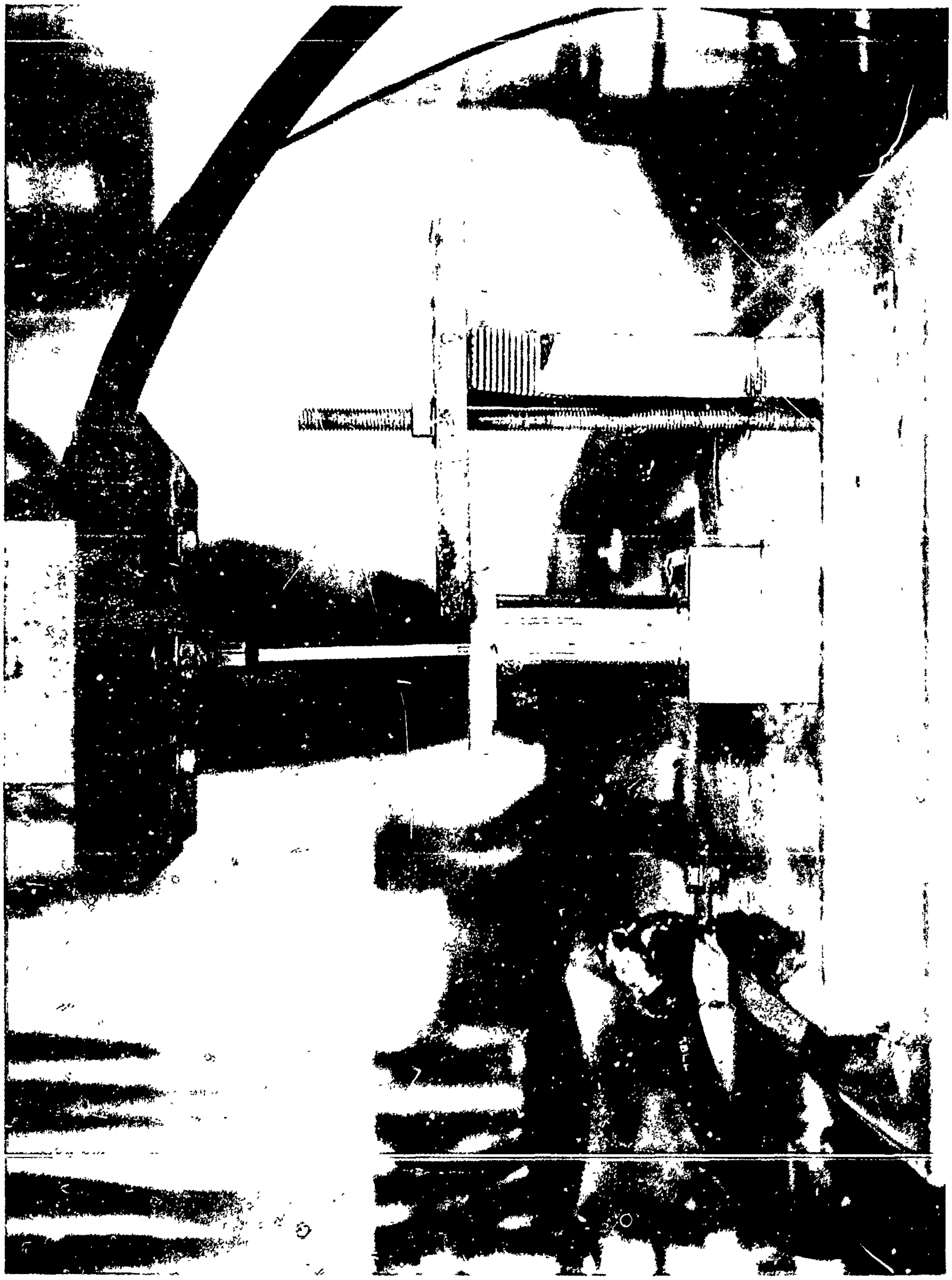


Figure 14. Electrochemical Gun-Drilling Test Appartus

TABLE VIII. ELECTROCHEMICAL GUN-DRILLING PARAMETERS FOR L-605 TESTS

Test No.	Volts	Amperes	Feed Rate in/min	Electrolyte Type	Electrolyte Pressure psi	Electrolyte Flow gal/min	Electrolyte Temperature °F	Remarks
1	15	30	0.100	A	100	a	100	Spark detect cut off at 0.047 inch deep, so reduced feed race to 0.075 inch/min. Electrode stopped. Electrode tip had small amount of insulation burnt off at tip.
2	15 15	25 20	0.500 0.035	A A	100 100	a a	100 100	Electrode stopped at 0.050 feed rate, so reduced it to 0.035. Electrode stopped at 0.490 inch deep. Could not restart because electrode shorted on sides of tip. Hole was 0.213 inch I.D. with very smooth side walls.
3	18 18 18	20 20 20	0.035 0.035 0.035	A A A	100 75 125	a a a	100 100 100	Electrode stopped at 0.755 inch deep, so reduced pressure to 75 psi. Could hear tool vibrating. Electrode stopped at 0.838 inch deep, so increased pressure to 125 psi. Electrode stopped at 0.842 inch deep. Insulation was gone around electrode tip because tip had shorted on sides. Hole was 0.230 inch I.D.
4	18	25	0.035	A	50	1.2	100	New electrode. Electrode stopped at 0.632 inch deep. Restarted and it stopped at 0.700 inch deep. Hole was 0.230 inch I.D.

TABLE VIII. ELECTROCHEMICAL GUN-DRILLING PARAMETERS FOR L-605 TESTS (Continued)

Test No.	Volts	Amperes	Feed Rate in/min	Electrolyte Type	Electrolyte Pressure psi	Electrolyte Flow gal/min	Electrolyte Temperature °F	Remarks
5	15	24	0.035	A	50	1.0	100	Used electrode with spacers on side wall. Electrode stopped at 0.365 inch deep. Hole was 0.220 inch I.D.
	15	28	0.035	A	50	1.0	100	Re-entered hole No. 2 using electrode with spacers and cut to 3.155 inch deep. This hole cut into hole No. 3, but looked good. Hole was 0.250 inch at exit.
6	16.5	25	0.035	A	50	1.2	100	Used electrode with spacers and plexiglass guide. Hole size was 0.230 inch I.D. at entrance and 0.260 inch I.D. at exit.
7	15	25 30 at 0.600 inch deep 30 at 2.500 inch deep	0.035	B	50	0.9	110	Workpiece was 2.860 inch long. Cut through workpiece and found hole size to be 0.235 inch I.D. at entrance and 0.270 inch at exit. Metal was plated out on electrode tip.

NOTE: Electrode tip was 0.200 inch in diameter. Test specimen was 3.175 inch long.

[a]Not measured.

TABLE IX. ELECTROCHEMICAL GUN-DRILLING PARAMETERS FOR TZM TESTS

Test No.	Volts	Amperes	Feed Rate in/min	Electrolyte Type	Pressure psi	Flow gal/min	Temperature °F	Remarks
1	15	28	0.035	A	50	1.2	100	Spark detect cut off at 0.300 inch deep. Could not restart. I.D. was 0.216 inch.
2	16	28	0.035	A	50	1.2	100	Changed electrode. Electrode stopped at 0.040 inch deep. Could not restart.
3	18 18 20	28 28 30	0.035 0.035 0.035	A A A	50 80 80	1.2 1.2 1.2	100 100 100	Changed electrode. Cut off at 0.097 inch deep, so increased pressure to 80 psi. Electrode stopped at 0.127 inch deep, so increased volts to 20. Electrode stopped at 0.147 inch deep. I.D. was 0.223 inch.
4	15 20 25	28 28 28	0.035 0.035 0.035	A A [illegible]	50 50 50	1.2 1.2 1.2	100 100 100	Used new guide to hold electrode. Electrode stopped at 0.048 inch deep, so increased volts to 20. Electrode stopped at 0.055 inch deep, so increased volts to 25. Electrode stopped at 0.098 inch deep.
5	20	35 40 at 1.2 inch deep 45 at 2.7 inch deep	0.035	A	50	1.2	115	Cut 3.534 inch deep. Insulation was gone around electrode tip. Hole shape was erratic due to missing insulation. Sidewall of hole was smooth indicating satisfactory cutting action.

TABLE IX. ELECTROCHEMICAL GUN-DRILLING PARAMETERS FOR TZM TESTS (Continued)

Test No.	Volts	Amperes	Feed Rate in/min	Electrolyte Type	Electrolyte Pressure psi	Electrolyte Flow gal/min	Electrolyte Temperature °F	Remarks
6	15	30 38 at 0.5 inch deep 42 at 1.0 inch deep 38 at 2.0 inch deep 50 at 3.0 inch deep	0.035	B	50	0.8	100	Tried nylon-insulated electrode. Amperes increased during cut. Electrode stopped at 3.218 inch deep because it had cut into adjacent hole. Metal had plated out on electrode tip causing hole to increase in size from 0.220 inch at entrance to 0.300 inch at bottom.
7	20	20	0.036	C	50	0.85	100	Cut to 3.159 inch deep. Hole size was 0.215 inch at entrance and 0.230 inch at exit.

NOTE: Electrode tip was 0.200 inch in diameter. Test specimen was 3.53 inch long.

TABLE X. ELECTROCHEMICAL GUN-DRILLING PARAMETERS FOR VM-103 TESTS

Test No.	Volts	Amperes	Feed Rate in/min	Electrolyte				Remarks
				Type	Pressure psi	Flow gal/min	Temperature °F	
1	15	20 30 at 3.0 inch deep	0.036	B	50	1.0	100	Amperes increased from 20 to 30 during cut. Metal plated out on electrode tip. Hole size was 0.235 inch at entrance and 0.300 inch at exit.
2	20	15	0.036	C	50	1.0	100	Hole looked good, but had cut into first hole. Hole size was 0.235 inch at entrance.
3	15	12	0.036	C	50	0.85	100	Part 2.670 inch long. Hole looked good, but had cut into center hole. Hole size was 0.220 inch at entrance and 0.235 inch at exit.

NOTE: Electrode tip was 0.200 inch in diameter. Test specimen was 3.15 inch long.

The stationary electrode approach for electrochemically rifling gun barrels uses a metal electrode insulated on the outside diameter which extends through the length of the barrel to be rifled. This electrode has grooves machined through the insulation which correspond to the dimensions and configuration of the desired rifling in the gun barrel. This electrode is placed inside the barrel to be rifled, electrolyte is pumped through the grooves in the electrode and, when current is applied, corresponding rifling grooves are electrochemically machined into the barrel (see Figures 15 and 16). This approach has the advantage of much greater economy, since the entire barrel is rifled at one time. The moving electrode travel would be limited by the electrochemical machining removal rate, and rifling would be much more time-consuming and costly.

3.4.1 STATIONARY ELECTRODE DEVELOPMENT

The initial objective of this portion of the program was to develop a satisfactory stationary electrode. Rifling tests were conducted using relatively short (approximately 6-inch) length 4130 steel tubes to determine optimum groove shape, evaluate various types of insulation materials and application techniques, and to establish electrochemical machining parameters. Machining tests conducted with aluminum electrodes revealed that the aluminum was eroded during machining operations, leaving rough edges at the corners of the electrode groove. Changing the electrode material to a tellurium-copper alloy eliminated this effect.

These initial tests were conducted with electrodes having a thin (0.002-inch) coating of epoxy insulation, which produced a smooth groove with a rough radius adjacent to the land area. As a result, electrodes were fabricated having a thick (0.025-inch) coating of insulation which produced grooves with a smooth radius. Therefore, all subsequent electrochemical machining rifling was accomplished with electrodes having the thick insulation coating.

In parallel to the above epoxy insulation thickness evaluation, tests were conducted using electrodes insulated with the thin (0.002-inch) coating of epoxy which had four different groove shapes (Figure 17), the objective being to determine the effect of groove shape on machining characteristics. No difference in machining characteristics among groove shapes was observed. Because groove shape "B" was most like conventional rifling, it was selected for all subsequent rifling.

A second parallel effort consisted of evaluating various electrode insulation materials to determine which was most suitable. Epoxy, acrylic, phenolic, polycarbonate, and acetal plastics were investigated. Of these, the epoxy and polycarbonate materials performed best. The final electrode design used a 0.169-inch-diameter tellurium-copper rod which was coated with epoxy using a fluidized-bed application technique. The electrode was coated oversize and then centerless-ground to the final 0.219-inch diameter.

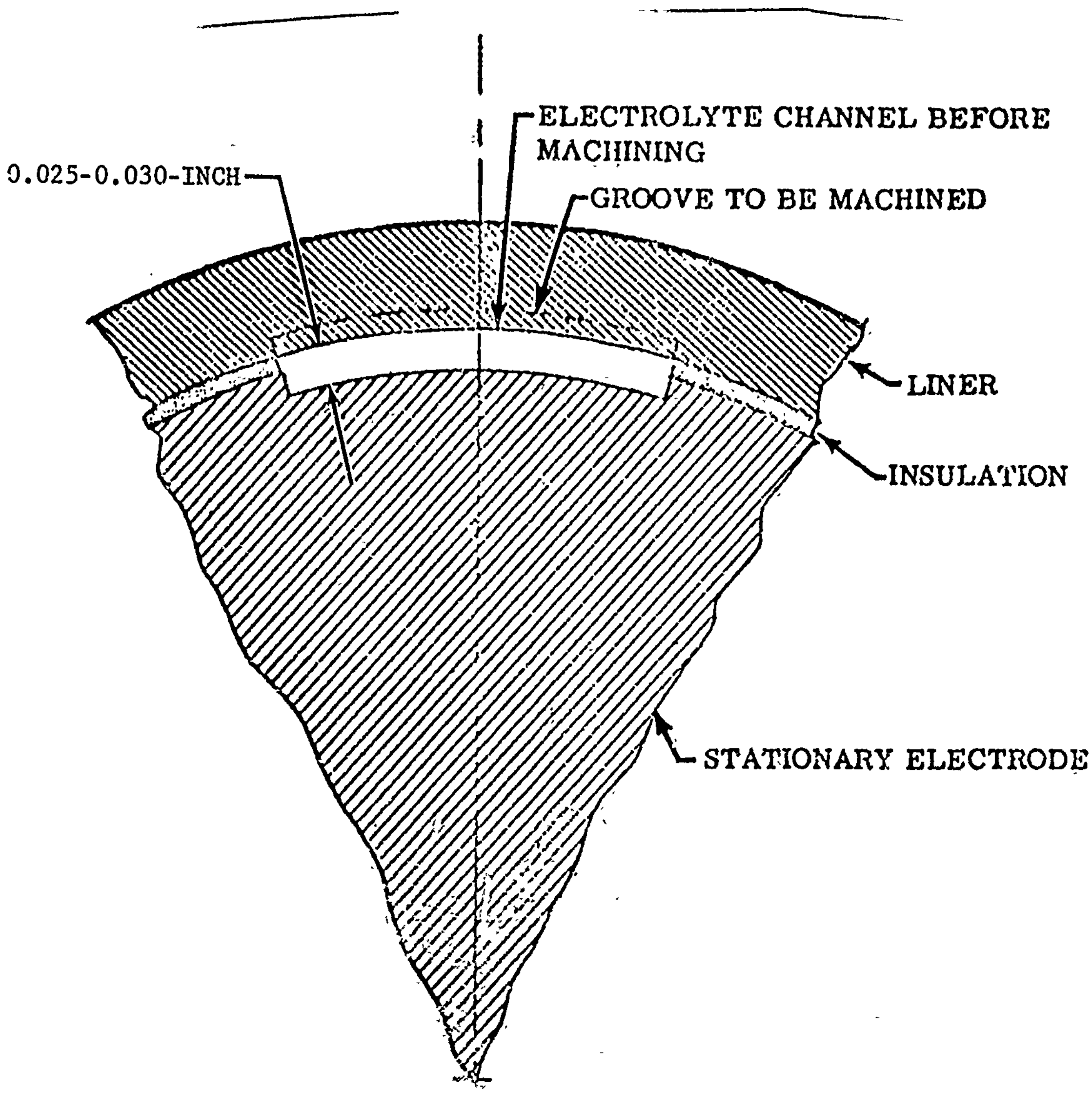


Figure 15. Sketch of Electrochemical Rifling Set-up With Stationary Electrode

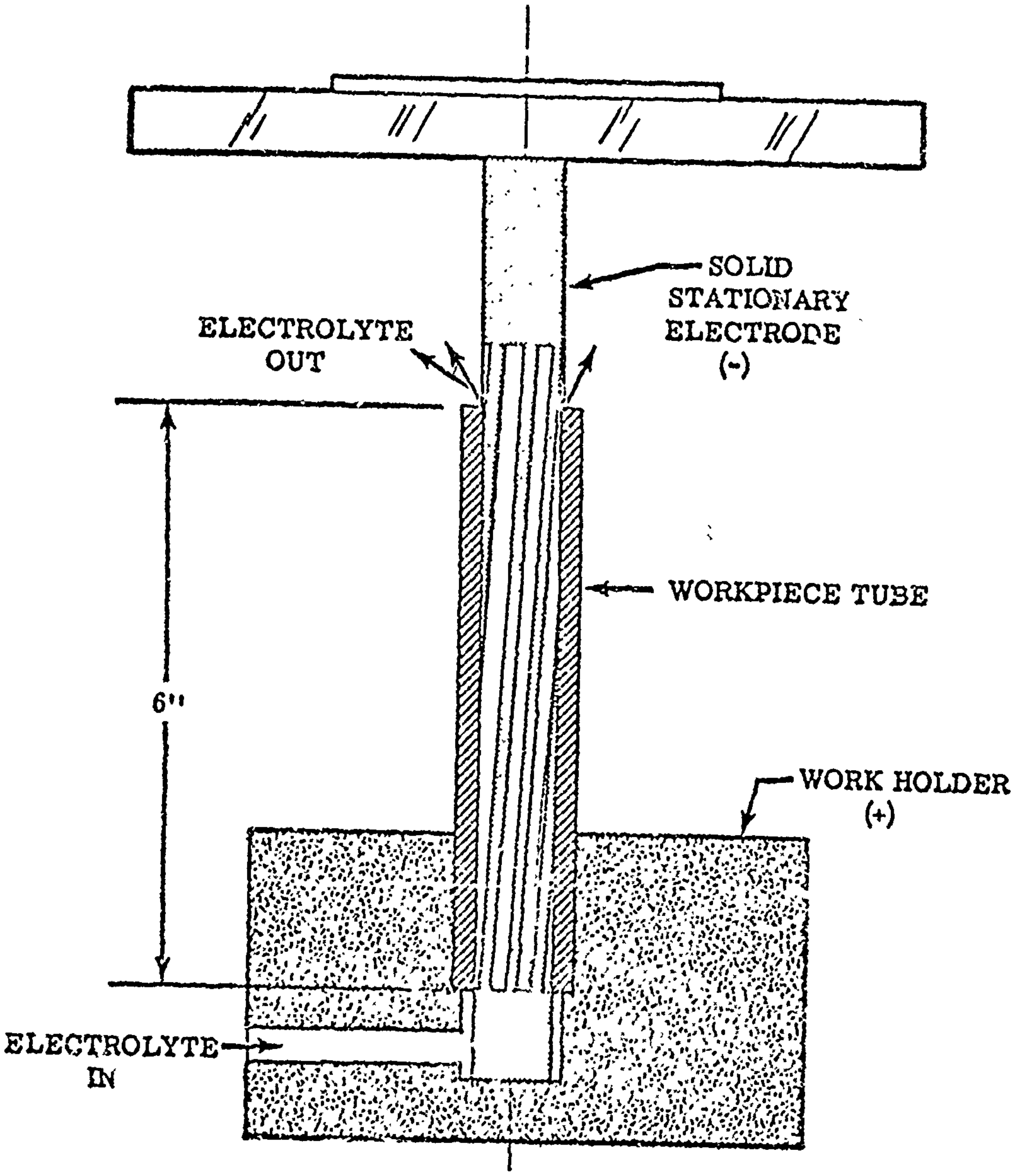


Figure 16. Sketch of Short-Length Electrochemical Rifling Tooling Utilizing the Stationary Electrode Technique

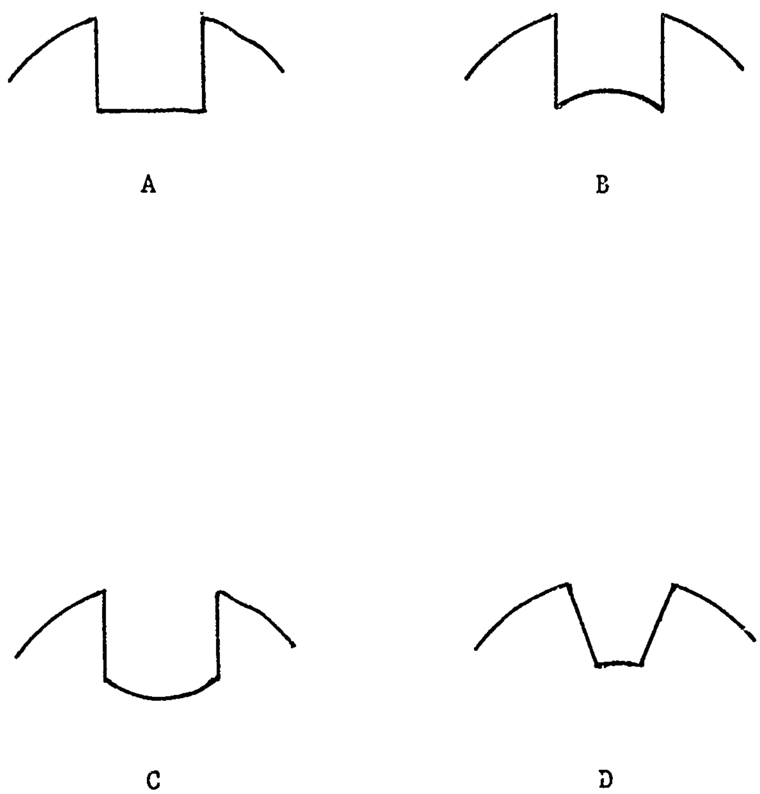


Figure 17. The Four Groove Shapes Evaluated

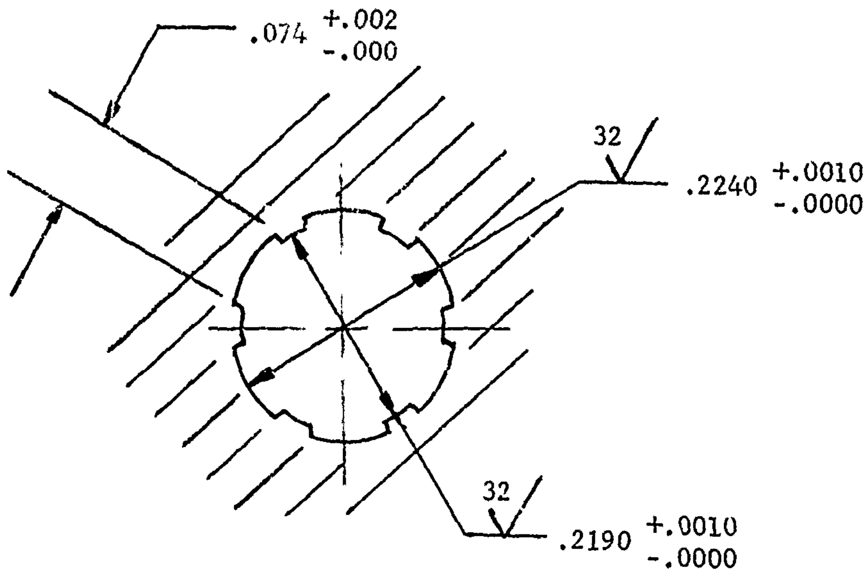
Rifling grooves 0.070-inch wide by 0.025-inch deep were then machined in the electrode.

3.4.2 ELECTROCHEMICAL MACHINING RIFLING SHORT LENGTH TRIALS

Having obtained a satisfactory stationary electrode, the next objective was to use the O.D. electrochemical rifling results described in subsection 3.1 to develop electrochemical machining parameters for internal rifling of the candidate liner materials. The required dimensions for .220 Swift rifling are shown in Figure 18.

Initially, four materials--L-605, VM-103, TZM and WC-3015--were tentatively selected as the deliverable barrel liner materials. In the course of the program, CG-27 and Inconel 718 were substituted for TZM and WC-3105 by mutual agreement with the contract monitor. TZM was dropped because of the poor erosion resistance it demonstrated during testing under Air Force Contract F08635-71-C-0181. WC-3015 was dropped because procurement of acceptable WC-3015 tubing could not be accomplished within the schedule of this program. However, WC-3015 is still an attractive future candidate since it was shown to be electrochemically machinable. CG-27 and Inconel 718 were selected as substitutes because of their known good electrochemical machinability, good erosion resistance (CG-27 was used successfully as a barrel material for the XM-140), and the fact that both were candidates for the GAU-8/A and other high performance weapons.

I.D. rifling tests, using short length barrels were run on five materials: 4130, L-605, VM-103, CG-27 and Inconel 718. These results, all successful, are given in Tables XI through XV, respectively. The electrochemical machining parameters developed in these tests were then used as a guide to fabricate the full length liners for the deliverable barrels under Phase II of the program.



Not To Scale

Rifling

6 Grooves

1 Turn in 10 inches - Right Hand

Figure 18. Sketch of .220 Swift Rifling

TABLE XI. INITIAL I.D. RIFLING PARAMETERS USED WITH STATIONARY ELECTRODE IN SHORT LENGTH 4130 SPECIMENS

Test No.	Volts	Amperes	Power-on Time sec	Electrolyte Type	Electrolyte Pressure psi	Electrolyte Temperature °F	Depth of Groove inch	Remarks
B-1	15	32	15	A	100	100		Used aluminum electrode. Edge of groove was rough.
B-2	20	55	10	A	100	100		Used aluminum electrode. Edge of groove was rough.
B-3	20	40	15	A	50	100	0.004	Used copper electrode with 0.025 inch-thick epoxy insulation and 0.074 inch-wide single groove on 3 inch-long workpiece. Groove looked good.
B-4	15	30	20	A	50	100	0.004	Same. Groove looked good.
B-5	10	20	30	A	50	100	0.004	Same. Groove looked good.
B-6	10	20	20	A	50	100	0.003	Same. Groove looked good.
B-7	10	19	20	A	25	100	0.003	Same. Groove looked good.
B-8	10	40	17	A	25	100	0.002	Used 3-groove electrode on 3 inch-long workpiece. Grooves looked good.
B-9	10	40	20	A	50	100	0.0025	Used 3-groove electrode. Grooves looked good.
B-10	10	70	19	A	50	100	0.0023	Used 3-groove electrode on 5 inch-long workpiece. Ran 6 grooves. Grooves looked good.
B-11	10	70	19	A	50	100	0.0023	Same as B-10. Looked good.
B-16	10	80	19	A	50	100	0.0025	Used 3-groove electrode with 0.070 inch-wide grooves on 5-1/4 inch-long workpiece. Looked good.

TABLE XII. INITIAL I.D. RIFLING PARAMETERS USED WITH STATIONARY ELECTRODE IN SHORT LENGTH L-605 SPECIMENS

Test No.	Volts	Amperes	Power-on Time sec	Electrolyte			Depth of Groove inch	Remarks
				Type	Pressure psi	Temperature °F		
1	15	20	15	a	50	100	0.0025	Very good
2	15	20	23	a	50	100	0.0035	Very good
3	15	20	240	a	50	100	0.019	Very good
5	10	18	19	b	50	100	0.0015	Very good
6[c]	10	65	30	b	50	100	0.00225	Very good. Used 3-groove electrode and cut six grooves.

Electrolyte Composition:

[a]0.37 lb/gal sodium chloride

[b]0.5 lb/gal sodium chloride

[c]All specimens were three inches long except No. 6 which was five inches long.

TABLE XIII. INITIAL I.D. RIFLING PARAMETERS USED WITH STATIONARY ELECTRODE IN SHORT LENGTH ALLOY 718 SPECIMENS

Test No.	Volts	Amperes	Power-on Time sec	Electrolyte			Depth of Groove inch	Remarks
				Type	Pressure psi	Temperature °F		
A-1	10	18	20	a	50	100	0.0018	Very good
A-2	10	19	28	a	50	100	0.0025	Very good

[a]0.5 lb/gal sodium chloride

NOTE: All specimens were three inches long.

TABLE XIV. INITIAL I.D. RIFLING PARAMETERS USED WITH STATIONARY ELECTRODE IN SHORT LENGTH VM-103 SPECIMENS

Test No.	Volts	Amperes	Power-on Time sec	Electrolyte			Depth of Groove inch	Remarks
				Type	Pressure psi	Temperature °F		
A-1	10	15	20	a	50	100	0.002	Surface rough.[e]
A-2	15	30	15	a	100	100	0.003	Surface rough.
A-3	10	20	30	b	50	75	0.0025	Surface rough.
A-4	15	30	20	b	50	75	0.0025	Surface rough.
B-1	15	22	20	c	30	75	0.0025	Surface rough.
B-2	20	30	15	c	30	75	0.0025	Surface rough.
B-3	20	60	15	d	30	75	0.0045	Surface rough.
B-4	15	45	15	d	30	75	0.005	Surface rough.

[a] 0.5 lb/gal sodium chloride
[b] 1.0 lb/gal sodium nitrate
[c] 1.0 lb/gal sodium chlorate
[d] 2.0 lb/gal sodium nitrate
[e] Surface of holes prior to rifling was rough and uneven.
NOTE: All specimens were three inches long.

TABLE XV. INITIAL I.D. RIFLING PARAMETERS USED WITH STATIONARY ELECTRODE IN SHORT LENGTH CG-27 SPECIMENS

Test No.	Volts	Amperes	Power-on Time sec	Electrolyte			Depth of Groove inch	Remarks
				Type	Pressure psi	Temperature °F		
A-1	10	15	20	a	50	100	0.002	Surface rough.
A-2	15	28	15	a	50	100	0.0025	Surface rough (slightly better).
A-3	20	40	10	a	100	100	0.002	Surface slightly rough.
A-4	10	20	20	b	50	75	0.0025	Surface rough.
A-5	15	30	20	b	50	75	0.0045	Surface rough.
B-1	15	25	20	c	30	75	0.0005	Surface rough. Machined most at edges of groove.
B-2	20	30	15	c	30	75	0.0005	Surface rough. Machined most at edges of groove.

Electrolyte Composition:

[a]0.5 lb/gal sodium chloride

[b]1.0 lb/gal sodium nitrate

[c]1.0 lb/gal sodium chlorate

NOTE: All specimens were three inches long.

SECTION IV

PHASE II - .220 SWIFT COMPOSITE BARREL FABRICATION

The goal for Phase II was to fabricate and deliver to the Air Force 12 barrels whose liners had been electrochemically rifled. The combinations of materials selected for these barrels are given in Table XVI.

4.1 FABRICATION OF ELECTROCHEMICALLY RIFLED FULL-LENGTH LINERS

4.1.1 ELECTROCHEMICAL MACHINING TOOLING DEVELOPMENT AND CHECKOUT

The design of the full-length (24-inch) tooling for electrochemical rifling, based on the results obtained in Phase I, is sketched in Figure 19. Photographs of the full-length tooling are given in Figures 20 and 21. Initial tests were conducted using a three-groove electrode which was indexed once to produce the six required rifle grooves. However, difficulty was encountered with insulation breakage, and a new electrode was fabricated having only two grooves. This electrode was indexed twice to produce the six grooves and was found to perform satisfactorily.

Using the successful two-groove electrode, two checkout 4130 full-length barrels (B-21 and B-23) were satisfactorily electrochemically rifled prior to fabrication of the remaining liners. After the first L-605 liner was rifled, a change in rifling twist from one turn in 14-inch to one turn in 10-inch was requested by the Air Force. A new electrode was fabricated, and two additional checkout 4130 full-length barrels (B-25 and B-26) were electrochemically rifled to the new twist. These two were equally satisfactory.

4.1.2 FABRICATION OF DELIVERABLE BARREL LINERS

Using conventional techniques, the gun barrel liners were gun-drilled, honed, and final machined on the O.D. They were then electrochemically rifled using the conditions given in Table XVII. A total of four barrels of L-605 and three barrels each of VM-103, CG-27, and Inconel 718 were electrochemically rifled. All full-length liners were air-gauged immediately after electrochemical rifling and again after assembly and final test firing. The two sets of data were identical within the error of the air gauge. Therefore, only the final set is reported (Table XVIII).

The bore data were very consistent, as expected, because the bore was honed to a constant I.D. before electrochemical rifling. All bore diameters were on the low side of the dimension tolerance, 0.219-to 0.220-inch, the vast majority being between 0.2187-inch and 0.2193-inch. The groove diameters were either in tolerance or within 0.0010-inch undersize. These

TABLE XVI. MATERIAL COMBINATIONS FOR DELIVERED BARRELS

Barrel Number	Liner Material	Jacket Material	Liner Code[a]
93-1	S.H.T.[b] VM-103	A-286	B-2
93-2	20% C.W.[c] VM-103	Pyromet X-15	B-C
93-3	20% C.W. VM-103	H-11	B-1
93-4	20% C.W. L-605	A-286	B-12
93-5	20% C.W. L-605	Pyromet X-15	B-11
93-6	20% C.W. L-605	H-11	B-9
93-7	CG-27	A-286	B-1
93-8	CG-27	Pyromet X-15	B-2
93-9	CG-27	H-11	B-3
93-10	Inconel 718	A-286	B-4
93-11	Inconel 718	Pyromet X-15	B-3
93-12	Inconel 718	H-11	B-5

[a]See Table XVII for correlation with electrochemical rifling conditions.

[b]S.H.T. - Solution heat treated only.

[c]20% C.W. - 20 percent reduction in diameter at room temperature by swaging.

NOTE: Insulation was H-203 in all cases.

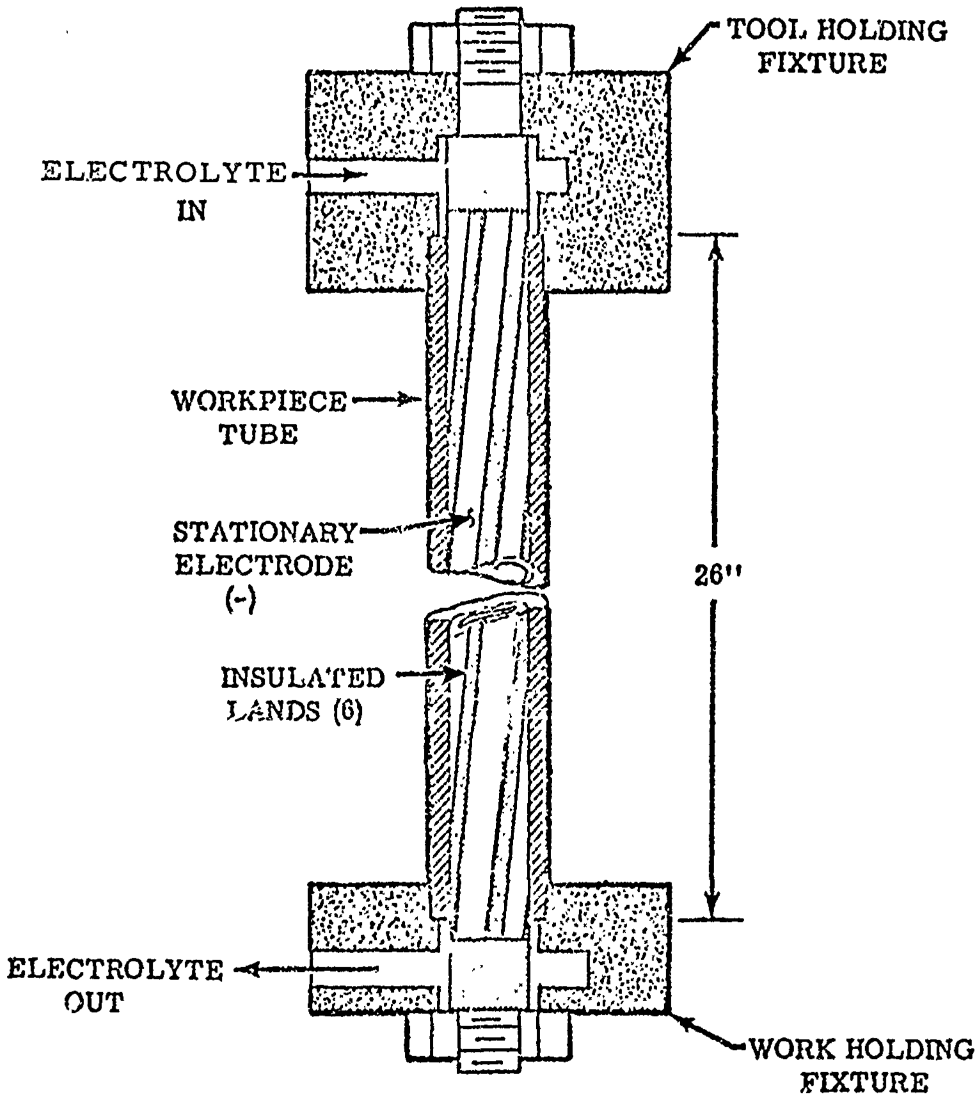


Figure 19. Sketch of Full-Length Electrochemical Rifling Tooling Utilizing the Stationary Electrode Technique

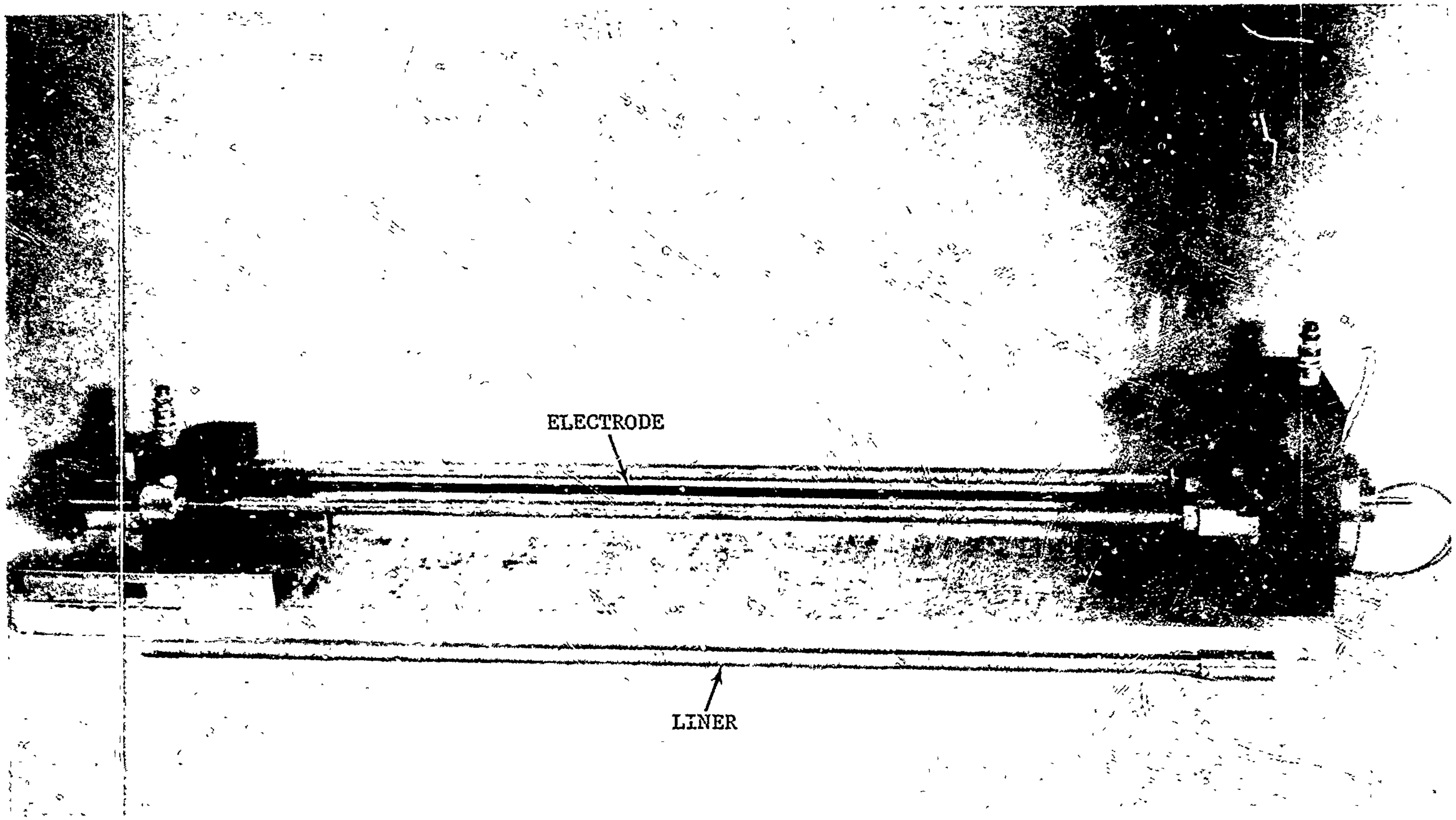


Figure 20. Tooling and Liner for Full-Length Electrochemical Rifling (Before Assembling)

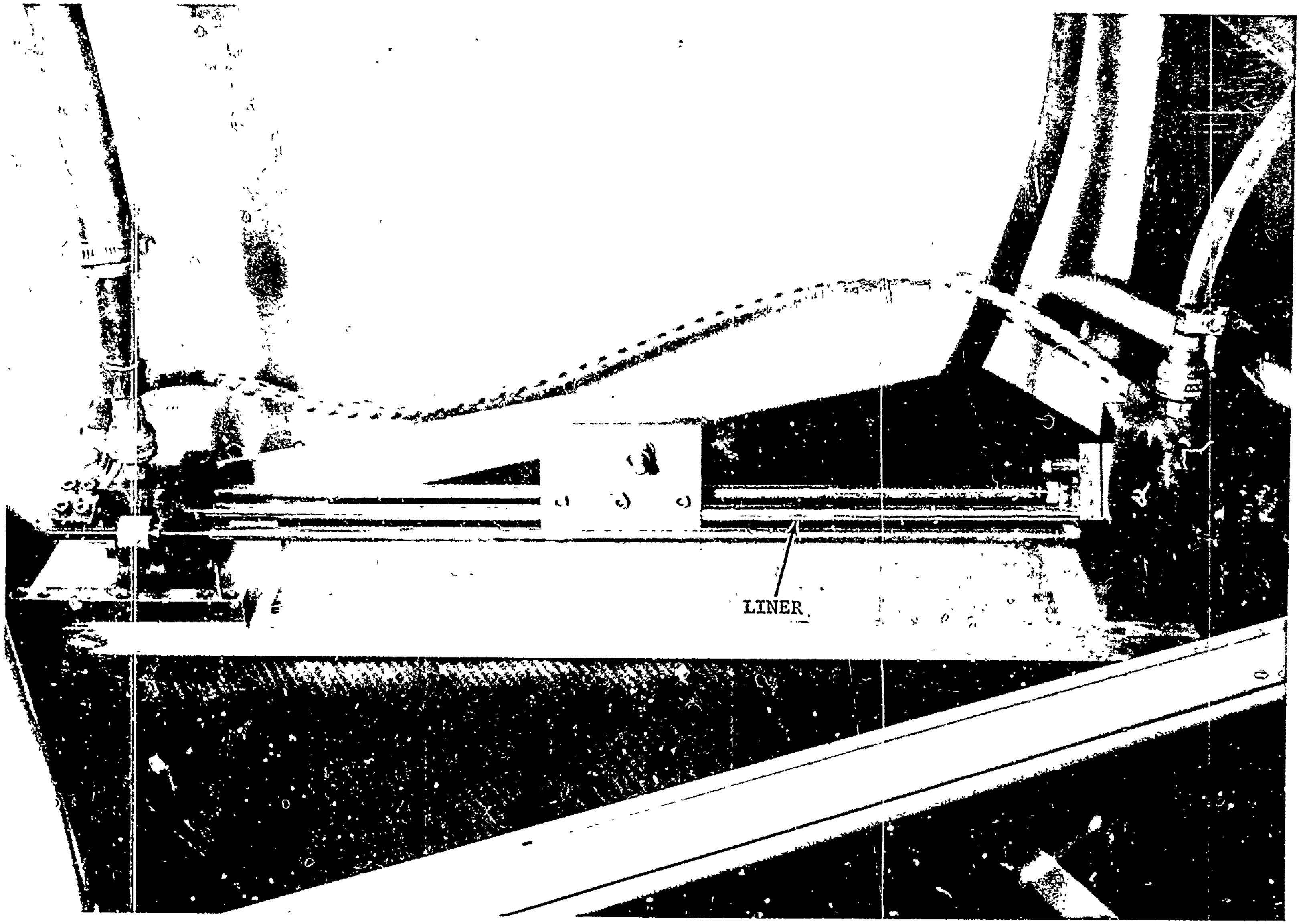


Figure 21. Assembled Tooling for Full-Length Electrochemical Rifling of Liners

TABLE XVII. ELECTROCHEMICAL RIFLING PARAMETERS FOR THE FULL LENGTH (24 INCH) LINERS

Material	Liner Number	Volts	Amperes	Power-on[a] Time sec	Electrolyte[b] Temperature °F	Electrolyte[b] Pressure psi	Remarks
4130	B-21	10	315	20	100	100	3-groove electrode[c]
	B-23	10	210	28	100	100	2-groove electrode[c]
	B-25	10	180	24	100	100	2-groove electrode[d]
	B-26	10	180	24	100	100	2-groove electrode[d]
L-605	B-8	10	160	48	100	100	2-groove electrode[c]
	B-9	10	160	48	100	100	2-groove electrode[d]
	[illegible]	10	160	56	100	100	2-groove electrode[d]
	B-11	10	160	56	100	100	2-groove electrode[d]
	B-12	10	150	52	100	100	2-groove electrode[d]
VM-103	B-1	15	250	24	100	100	2-groove electrode[d]
	B-2	15	250	24	100	100	2-groove electrode[de]
	B-C	15	255	24	100	100	2-groove electrode[de]

[a] All barrels run 2 seconds current on, 5 seconds current off. Electrolyte flow direction reversed after each 4 seconds of power-on time.
[b] Electrolyte composition was 1/2 lb/gal NaCl.
[c] Electrode groove twist was 1 turn in 14 inches.
[d] Electrode groove twist was 1 turn in 10 inches.
[e] Electrode fit very tight in barrel.

TABLE XVII. ELECTROCHEMICAL RIFLING PARAMETERS FOR THE FULL LENGTH (24-INCH) LINERS (Continued)

Material	Liner Number	Volts	Amperes	Power-on[a] Time sec	Electrolyte[b] Temperature °F	Electrolyte[b] Pressure psi	Remarks
CG-27	B-1	15	280	24	100	100	2-groove electrode[d]
	B-2	15	270	26	100	100	2-groove electrode[d]
	B-3	15	270	26	100	100	2-groove electrode[d]
Inconel 718	B-3						
	(4 grooves)	10	150	44	100	100	2-groove electrode[d]
	(2 grooves)	15	260	28	100	100	
	B-4	15	250	36	100	100	2-groove electrode[d]
	B-5	15	250	36	100	100	2-groove electrode[d]

[a] All barrels run 2 seconds current on, 5 seconds current off. Electrolyte flow direction reversed after each 4 seconds of power-on time.
[b] Electrolyte composition was 1/2 lb/gal NaCl.
[c] Electrode groove twist was 1 turn in 14 inches.
[d] Electrode groove twist was 1 turn in 10 inches.

TABLE XVIII. FINAL BORE AND GROOVE MEASUREMENTS MADE AFTER TEST FIRING

93-1 (A-286 Jacket: S.H.T. VM-103 Insert)						
	Distance From Rear of Breech in Inches					
	3	5	7	9	16	20
Groove A	0.2232	0.2239	0.2245	0.2249	0.2249	0.2242
Groove B	0.2234	0.2246	0.2246	0.2249	0.2250	0.2242
Groove C	0.2233	0.2244	0.2245	0.2251	0.2251	0.2247
Land A	a	a	a	a	a	a
Land B	a	a	a	a	a	a
Land C	a	a	a	a	a	a
(Pyromet X-15 Jacket; 20% C.W. VM-103 Insert) 93-2						
Groove A	0.2232	0.2242	0.2250	0.2254	0.2248	0.2236
Groove B	0.2235	0.2244	0.2253	0.2259	0.2251	0.2240
Groove C	0.2234	0.2241	0.2250	0.2256	0.2256	0.2239
Land A	0.2185	0.2185	0.2191	0.2193	a	a
Land B	a	a	a	a	a	a
Land C	a	a	a	a	a	a
Average Groove Depth	0.0025	0.0029	0.0030	0.0032	b	b

[a]Air gage would not fit into bore at this station.
[b]Not calculated.

TABLE XVIII. FINAL BORE AND GROOVE MEASUREMENTS MADE AFTER TEST FIRING (Continued)

93-3 (H-11 Jacket; 20% C.W. VM-103 Insert)						
	Distance From Rear of Breech in Inches					
	3	5	7	9	16	20
Groove A	0.2240	0.2245	0.2246	0.2245	0.2251	0.2247
Groove B	0.2239	0.2241	0.2243	0.2246	0.2245	0.2241
Groove C	0.2238	0.2241	0.2244	0.2247	0.2250	0.2246
Land A	0.2188	0.2187	0.2187	0.2188	0.2186	0.2188
Land B	0.2187	0.2187	0.2187	0.2188	0.2186	0.2187
Land C	0.2187	0.2187	0.2187	0.2189	0.2186	0.2188
Average Groove Depth	0.0026	0.0028	0.0029	0.0030	0.0032	0.0029
(A-286 Jacket; 20% C.W. L-605 Insert) 93-4						
Groove A	0.2233	0.2233	0.2235	0.2238	0.2241	0.2236
Groove B	0.2234	0.2234	0.2236	0.2240	0.2242	0.2236
Groove C	0.2232	0.2233	0.2235	0.2239	0.2242	0.2236
Land A	0.2186	0.2185	0.2187	0.2185	0.2186	0.2189
Land B	0.2187	0.2186	0.2185	0.2187	0.2185	0.2187
Land C	0.2186	0.2186	0.2186	0.2185	0.2186	0.2187
Average Groove Depth	0.0024	0.0024	0.0025	0.0027	0.0028	0.0024

TABLE XVIII. FINAL BORE AND GROOVE MEASUREMENTS MADE AFTER TEST FIRING (Continued)

93-5 (Pyromet X-15 Jacket; 20% C.W. L-605 Insert)	Distance From Rear of Breech in Inches					
	3	5	7	9	16	20
Groove A	0.2241	0.2245	0.2245	0.2246	0.2247	0.2246
Groove B	0.2241	0.2245	0.2249	0.2243	0.2248	0.2248
Groove C	0.2240	0.2241	0.2243	0.2244	0.2250	0.2249
Land A	0.2187	0.2187	0.2187	0.2187	0.2187	0.2191
Land B	0.2185	0.2188	0.2187	0.2187	0.2189	0.2191
Land C	0.2187	0.2188	0.2188	0.2188	0.2190	0.2191
Average Groove Depth	0.0028	0.0028	0.0030	0.0029	0.0030	0.0029
93-6 (H-11 Jacket; 20% C.W. L-605 Insert)						
Groove A	0.2238	0.2240	0.2240	0.2239	0.2245	0.2239
Groove B	0.2238	0.2241	0.2241	0.2240	0.2245	0.2242
Groove C	0.2238	0.2239	0.2241	0.2242	0.2245	0.2241
Land A	0.2196	0.2191	0.2187	0.2187	0.2188	0.2190
Land B	0.2189	0.2188	0.2188	0.2187	0.2189	0.2188
Land C	0.2188	0.2190	0.2187	0.2187	0.2187	0.2188
Average Groove Depth	0.0024	0.0025	0.0027	0.0027	0.0029	0.0026

TABLE XVIII. FINAL BORE AND GROOVE MEASUREMENTS MADE AFTER TEST FIRING (Continued)

	Distance From Rear of Breech in Inches					
93-7 (A-286 Jacket; CG-27 Insert)	3	5	7	9	16	20
Groove A	0.2230	0.2232	0.2236	0.2236	0.2242	0.2242
Groove B	0.2230	0.2235	0.2237	0.2243	0.2241	0.2244
Groove C	0.2230	0.2236	0.2241	0.2244	0.2240	0.2245
Land A	0.2189	0.2190	0.2190	0.2191	0.2191	0.2195
Land B	0.2191	0.2191	0.2190	0.2191	0.2191	0.2192
Land C	0.2190	0.2191	0.2191	0.2191	0.2192	0.2195
Average Groove Depth	0.0020	0.0022	0.0024	0.0025	0.0025	0.0025
93-8 (Pyromet X-15 Jacket: CG-27 Insert)						
Groove A	0.2237	0.2237	0.2245	0.2242	0.2244	0.2237
Groove B	0.2237	0.2239	0.2242	0.2247	0.2236	0.2238
Groove C	0.2238	0.2244	0.2244	0.2248	0.2239	0.2240
Land A	0.2193	0.2193	0.2192	0.2194	0.2195	0.2195
Land B	0.2193	0.2195	0.2197	0.2194	0.2193	0.2191
Land C	0.2194	0.2192	0.2195	0.2195	0.2193	0.2191
Average Groove Depth	0.0022	0.0024	0.0025	0.0026	0.0023	0.0023

TABLE XVIII. FINAL BORE AND GROOVE MEASUREMENTS MADE AFTER TEST FIRING (Continued)

93-9 (H-11 Jacket; CG-27 Insert)						
	Distance From Rear of Breech in Inches					
	3	5	7	9	16	20
Groove A	0.2236	0.2241	0.2244	0.2247	0.2242	0.2240
Groove B	0.2236	0.2241	0.2243	0.2246	0.2242	0.2239
Groove C	0.2237	0.2242	0.2244	0.2247	0.2242	0.2241
Land A	0.2190	0.2190	0.2190	0.2191	0.2187	0.2187
Land B	0.2190	0.2190	0.2190	0.2189	0.2188	0.2188
Land C	0.2191	0.2190	0.2190	0.2190	0.2187	0.2188
Average Groove Depth	0.0023	0.0026	0.0027	0.0029	0.0028	0.0026

93-10 (A-286 Jacket; 718 Insert)	3	5	7	9	16	20
Groove A	0.2238	0.2243	0.2245	0.2246	0.2246	0.2245
Groove B	0.2239	0.2243	0.2247	0.2248	0.2248	0.2245
Groove C	0.2241	0.2244	0.2247	0.2248	0.2248	0.2247
Land A	0.2187	0.2185	0.2185	0.2185	0.2187	0.2188
Land B	0.2187	0.2185	0.2185	0.2185	0.2187	0.2187
Land C	0.2188	0.2185	0.2185	0.2185	0.2188	0.2188
Average Groove Depth	0.0026	0.0028	0.0031	0.0031	0.0030	0.0029

TABLE XVIII. FINAL BORE AND GROOVE MEASUREMENTS MADE AFTER TEST FIRING (Concluded)

93-11 (Pyromet X-15 Jacket; 718 Insert)						
	Distance From Rear of Breech in Inches					
	3	5	7	9	16	20
Groove A	0.2233	0.2245	0.2245	0.2244	0.2239	0.2237
Groove B	0.2233	0.2242	0.2240	0.2239	0.2234	0.2234
Groove C	0.2234	0.2243	0.2242	0.2240	0.2237	0.2236
Land A	0.2192	0.2195	0.2193	0.2192	0.2187	0.2187
Land B	0.2190	0.2196	0.2193	0.2193	0.2187	0.2189
Land C	0.2191	0.2196	0.2194	0.2190	0.2187	0.2187
Average Groove Depth	0.0021	0.0024	0.0025	0.0025	0.0025	0.0024
93-12 (H-11 Jacket; 718 Insert)						
Groove A	0.2247	0.2247	0.2250	0.2255	0.2257	0.2255
Groove B	0.2249	0.2252	0.2253	0.2255	0.2255	0.2254
Groove C	0.2250	0.2253	0.2253	0.2256	0.2256	0.2255
Land A	0.2194	0.2191	0.2191	0.2191	0.2189	0.2192
Land B	0.2193	0.2192	0.2190	0.2189	0.2188	0.2193
Land C	0.2194	0.2101	0.2190	0.2189	0.2189	0.2193
Average Groove Depth	0.0028	0.0030	0.0031	0.0033	0.0034	0.0031

two measurements, the bore and groove diameters, were averaged, subtracted, and divided by two to obtain the average groove depth (Table XVIII). A tendency of the electrochemical rifling process to produce shallower grooves at each end of the barrel was readily observed. An attempt to counteract this effect was made by trimming one inch of length from each end; however, the data show this did not eliminate the effect completely. In all barrel liners, station 3 has the shallowest groove depth. Groove depths at station 20 were less than those at station 16 in eight of ten barrel liners (they were equal for the remaining two liners). All barrels met the groove depth tolerance of 0.002 to 0.003 inch except 93-10 and 93-12, which were too deep by 0.0001 inch and 0.0004 inch, respectively, at some stations. Since the barrels were electrochemically rifled separately, it is thought that better control would be achieved if they were run in batches, although the dimensional control achieved here is still good.

All VM-103 liners were gun-drilled using the electrical discharge machining process because conventional machining has been proven to be too slow to be economically feasible. The bores were drilled with a half-length electrode - one-half was drilled starting from one end and the other half was drilled from the other end. This resulted in a mismatch at the middle of the barrel length where the two holes met. Final honing did not eliminate this mismatch entirely which existed in all of the VM-103 barrels delivered. It is suggested that during final testing of the barrels this area be given special scrutiny.

4.2 ASSEMBLY, DRAWING, AND FINAL MACHINING

The electrochemically rifled liners were processed according to the flow chart (Figure 22). This process for fabricating full length insulated composite barrels, which was developed under Contract F08635-71-C-0181, includes a drawing operation wherein the insulated liners are slip fitted into the barrel jackets, and the assembly is drawn through a sizing die to collapse the jacket down onto the liner, thereby providing a good mechanical bond. Photographs of the draw bench and sizing dies are shown in Figures 23 and 24, respectively. The H-11 jackets were heated to ~800°F prior to assembly, and then immediately drawn. Subsequent cooling of the jacket further improved the degree of mechanical bonding. The other two jacket materials, Pyromet X-15 and A-286, were drawn at 450°F and ambient temperature, respectively, then subsequently subjected to the aging treatments indicated in Figure 22. The aging treatments caused the jackets to contract further (~0.0005 in./in. for the Pyromet X-15 and ~0.001 in./in. for the A-286), thereby increasing the mechanical bond strength. Since the liners had already been partially aged as discussed below, it was assumed that further liner shrinkage was negligible. Further details of the drawing

Procure Jacket Material

Heat Treat (H-11 only)

Gun Drill, Counterbore, Hone

O. D. Machine For Drawing

Procure Liner Material

AGE
- CG-27 With H-11: 1450°F 16 hr + 1200°F 16 hr
- CG-27 With A-286 and Pyromet X-15: 1450°F 16 hr only.
- Inconel 718 With H-11: 1325°F 8 hr, F.C. to 1150°F 8 hrs.
- Inconel 718 With A-286: 1325°F 4 hr only.
- Inconel 718 With Pyromet X-15: 1325°F 6 hr only.

Cold Swage (VM-103, L-605 only)

Conventional Gun Drill and Hone (EDM VM-103)

Electrochemical Rifle

Straighten (If Required)

Air Gage

O.D. Machine For Insulation

Insulate

O.D. Grind and Thread For Assembly

Assemble

Draw

AGE
- A-286 Jacket: 1325°F 6 hr
- Pyromet X-15: 1100°F 4 hr + 1250°F 4 hr
- H-11: none

O.D. Machine

Attach Breech Retainers

Chamber

Final Inspect

Proof - Test Fire

Black Oxide Conversion Coat
- H-11: MIL-C-13924, Class 3.3.1
- Pyromet X-15: MIL-C-13924, Class 3.3.3
- A-286: MIL-C-13924, Class 3.3.3

Air Gage

Ship to Eglin Air Force Base

Figure 22. Process Flow Sheet for Electrochemically Rifled Composite Barrel Fabrication

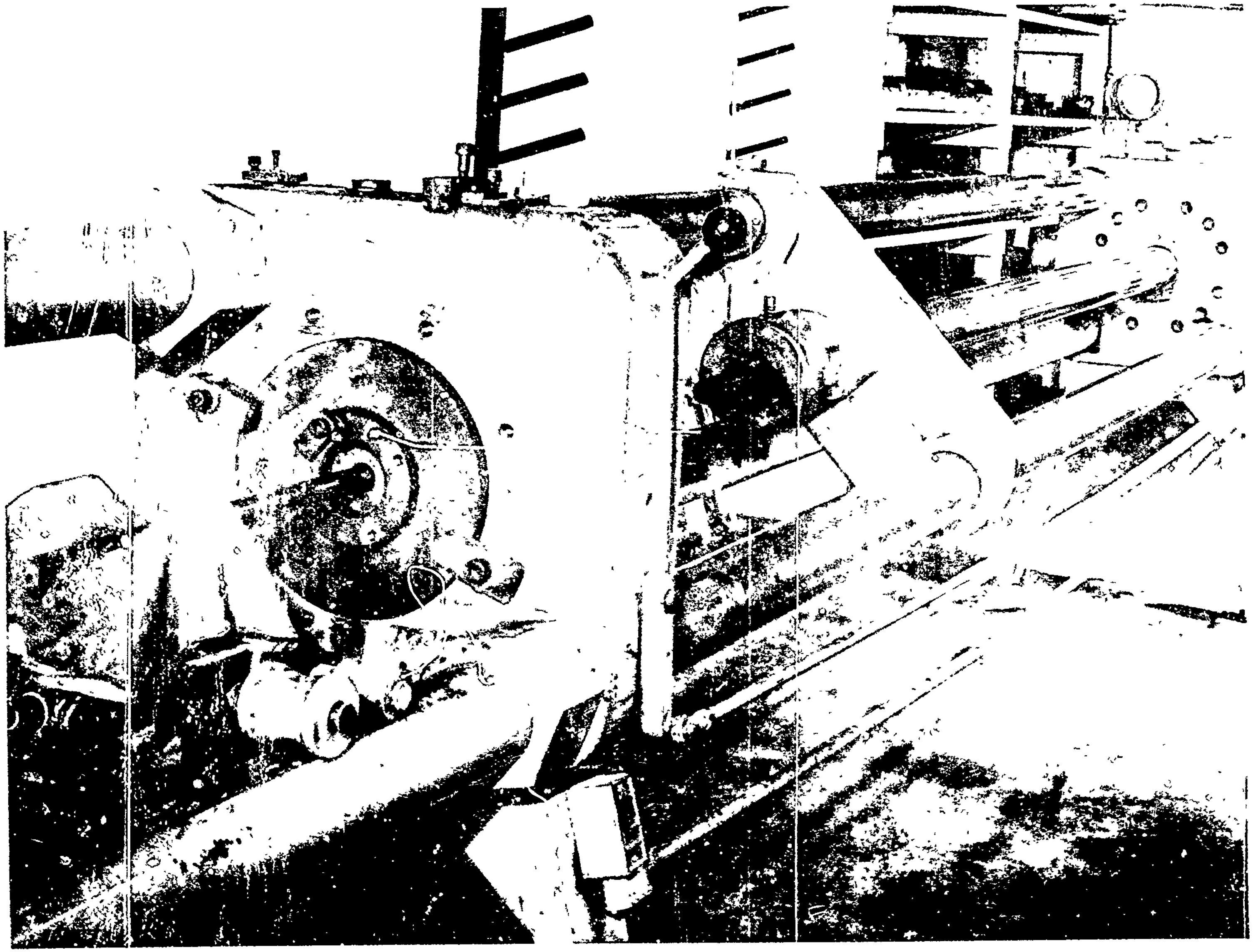


Figure 23. Drawing Equipment Utilized for Composite Barrels

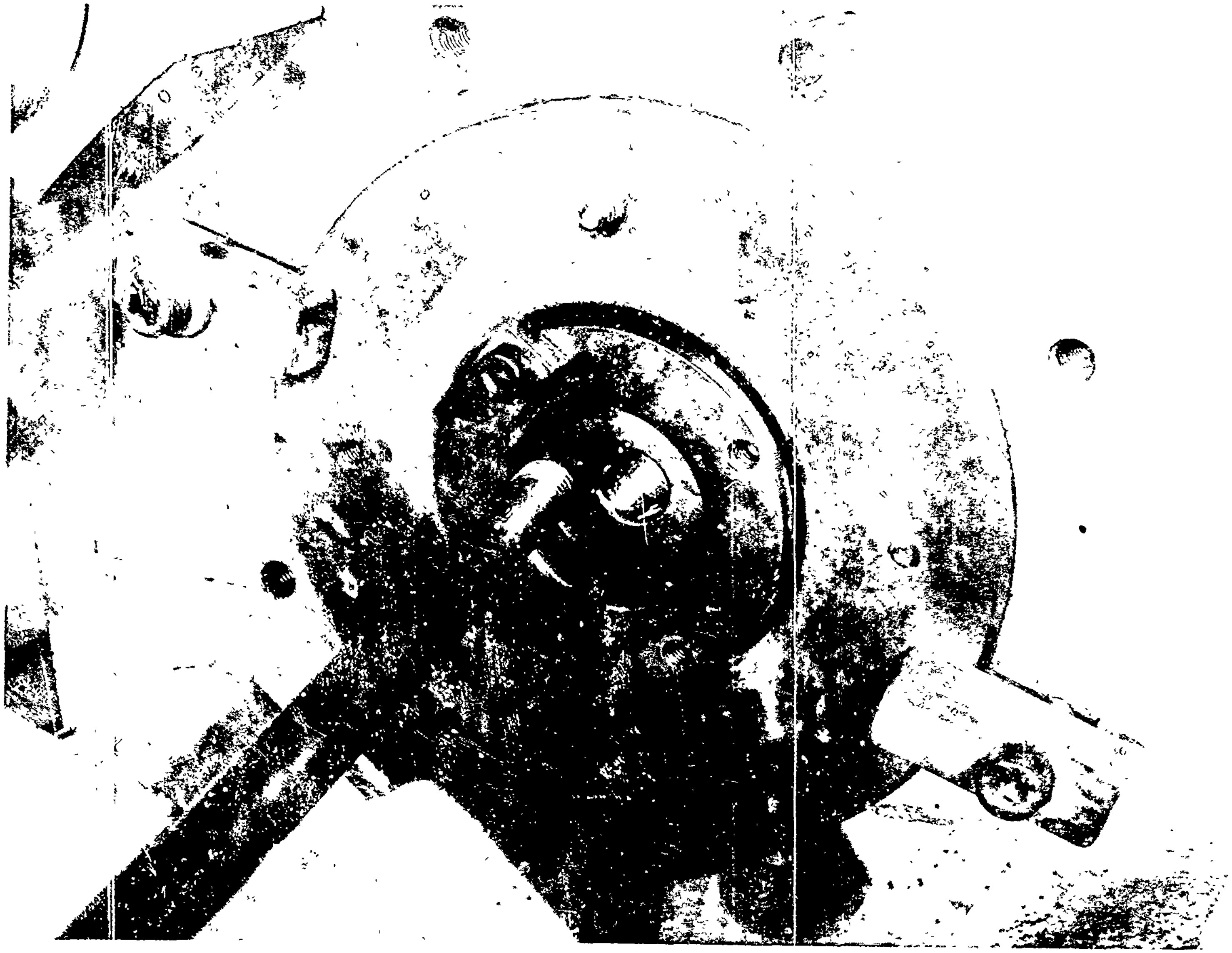


Figure 24. Drawing Die Utilized for Composite Barrels

process and how it was developed are included in the final report of Contract F08635-71-C-0181. A sketch of the fully assembled barrel is given in Figure 25.

It should be noted that each liner material was delivered in several slightly varying heat-treated conditions, depending upon its respective jacket material. This was necessary to make sure the fabrication sequence did not overage the liner material. For instance, the CG-27 liner with the H-11 jacket was aged per AMS 5633 (1450°F for 16 hours, air cool, 1200°F 16 hours). With the A-286 jacket, it was aged at 1450°F for 16 hours, assembled, and then given the A-286 age (1325°F 16 hours). With the Pyromet X-15 jacket, it was again single-aged at 1450°F for 16 hours, assembled, and then given the Pyromet X-15 age (1100°F for 4 hours, air cool, 1250°F for 4 hours). These alternate aging treatments were selected without availability of time-temperature aging data but were estimated to result in properties similar to those achieved by standard processes. Further efforts to optimize combination aging treatments for jacket and liner materials may be worthy of future consideration.

The barrels were conventionally O.D. machined, chambered, and inspected. They were then subjected to a ten-round proof test firing burst on a MG-3 machine gun at approximately 1150 spm. Borescope examination and black oxide treatments followed. A sealing arrangement was constructed to prevent the black oxide solution from reaching the bore or the insulation between the liner and jacket. Finally, the barrels were air gauged (Table XVIII), coated with a preservative oil, packaged, and shipped to the Air Force.

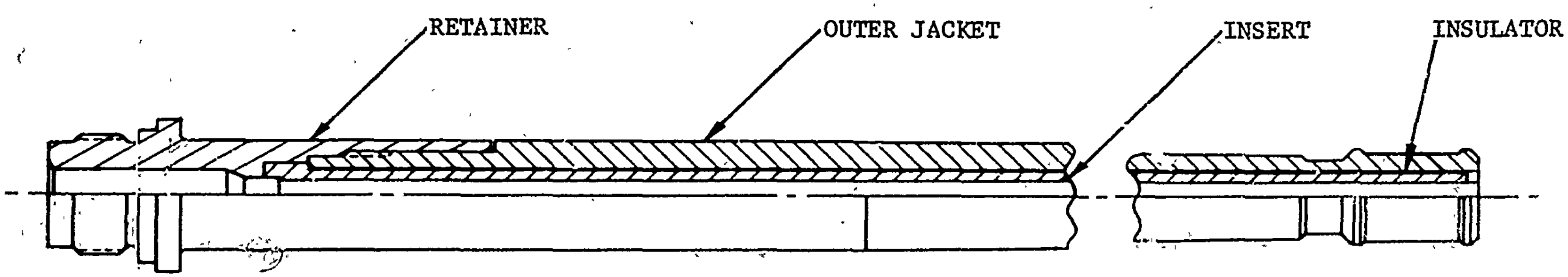


Figure 25. .220 Swift/MG-3 Barrel

REFERENCES

1. McMahon, D., "An Electrochemical Machining Machine Design for Deep-Hole Boring". Society of Manufacturing Engineers, MR77-541, 1972.

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USN WPNS LAB CODE TR	1
USN ORD LAB TECH LIB	1
USN ORD LAB CODE 730	2
NAV ORD STN TECH LIB	1
USN WPN CTR CODE 753	2
USN WPN CTR CODE 4585	1
57 FTR SPN WG (FWOA)	1
USN RSCH LAB CODE 2027	1
USN RSCH LAB CODE 5180	1
UNIV OF CA LRL CHEM DEPT	1
UNIV OF CA LRL TECH INFO DEPT	1
LOS ALAMOS SCI LAB	1
BATTELLE MEM INST	1
DDC	2
PHILCO-FORD CORP	2
HQ PACAF (IGY)	1
TRADOC/ADTC/DO	1
DL	1
DLOSL	2
DLDG	20

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13. ABSTRACT

A 16-month program was conducted to advance high performance gun barrel technology by developing an electrochemical machining process for rifling high performance barrel liner materials. A total of 15 electrolytes and numerous electrochemical machining parameters were evaluated in conducting electrochemical machinability studies on iron-nickel-base, nickel-base, and cobalt-base superalloys, and on refractory alloys of columbium, molybdenum, tantalum, and tungsten.

Four materials (L-605, VM-103, CG-27, and alloy 718) were selected for electrochemical rifling and fabrication into caliber .220-Swift barrel liners. The rifled liners were insulated externally and assembled into outer barrel jackets using a drawing process, thus producing insulated composite test barrels. A total of 12 test barrels compatible with an MG-3 machine gun, representing the four liner materials and three jacket materials (H-11, A-286, and Pyromet X-15), were fabricated and delivered to the Air Force. The results of this program indicated that electrochemical machining is a feasible process for obtaining high quality and low cost rifling, and that extrapolation of this process to larger calibers appears feasible.

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Equilibrium temperature gun						
Ordnance concepts						
Gun concepts						
Electrochemical Machining						

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